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Numerical Modelling of Electro-Discharge Machining Process using Moving Mesh Feature

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Abstract

This paper is concerned with numerical modelling of Electro Discharge Machining (EDM) process using moving mesh feature. Coefficient of erosion was defined and found to be constant using analytical equations. This was validated by conducting experiments on electro discharge machining. Then, the machining process was modelled in software using the coefficient of erosion. When the same conditions were applied in the real time machining, the results obtained were in good agreement with that of the software results. The application of software modelling was demonstrated to determine the process efficiency of drilling process. The process efficiency helps to find out if there is any scope for improvement in process and therefore enhanced productivity. Also, machining time which is one of the critical factors in micro-EDM process was predicted using software. This greatly saves time and resources and also, the difficulty in manufacture of micro sized electrodes for research is greatly reduced. A comparison study was performed with the use of conventional and concentric electrode for drilling concentric micro size holes. It was concluded that reduced machining time and perfect concentricity was observed when conventional electrodes were replaced by concentric electrodes. Yet another study was performed to justify the reduction in machining time due to usage of conductivity enhancement rings in the direction of passage of current to enhance current flow by avoiding air gap insulation. Thus, software modelling helps to perform research by predicting machining time without the need of real time experimentation.

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Keywords: Electro-discharge machining; Coefficient of erosion; Numerical modelling; Process efficiency; Micro-EDM

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Nomenclature

- **K**: coefficient of erosion (m³/As)
- **V**: voltage (V)
- **I**: supply current (A)
- **t**: time of passage of current (s)
- **Q**: heat generated (W)
- **R**: resistance (ohm)
- **V_v**: total volume of material removed (m³)
- **N**: number of pulses
- **T**: cycle time (s)
- **T_{on}**: pulse on time (s)
- **T_{off}**: pulse off time (s)
- **E_s**: energy due to single pulse (W)
- **MRR**: material removal rate (mm³/min)
- **W_1**: weight of the plate before machining (g)
- **W_2**: weight of the plate after machining (g)
- **ΔW**: difference of weights (g)
- **ΔV**: difference in volume (m³)
- **J**: current density (A/m²)
- **U**: mesh velocity (m/s)
- **V_v**: volume of material removed (m³)
- **RC**: resistance capacitance circuit
- **D_1, D_2**: diameter of concentric holes (mm)
- **L_1, L_2**: depth of concentric holes (mm)
- **A**: contact area of concentric electrode (mm²)

Greek symbols

- **ρ**: resistivity of material (ohm.m)
- **ω**: pulse ratio
- **μ**: unit volume of material removed (m³)
- **£**: density of material (kg/m³)

1. Introduction

Electric Discharge Machining (EDM) is a non-traditional machining process which uses the spark generated due to passage of current for machining the components under controlled conditions. But only electrically conductive materials can be machined as it involves passage of current. This non traditional machining process produces accurate finish of components. The different types of EDM are die sinker EDM and wire EDM. One of the recent advancements of the process is micro-EDM which has the ability to machine micron size cavities and holes in the work piece. The research started with the study of influence of machining parameters on EDM [1]. It was concluded that metal removal rate and surface roughness increased with increase in current. After finding out the influence of various machining parameters, research focussed on improving the performance parameters like material removal rate, improved surface finish and reduced wear of tool. One such attempt was carried out by Dhananjay, Pradhan and Jayswal [2] to improve the performance parameter by manufacture of electrodes from copper and aluminium. They found that copper electrode gives good surface finish of component as compared to aluminium. Also, they found that surface roughness increases with increase in pulse on time for all values of peak current. One of the critical issues of EDM is the machining time. The effect of surface roughness on machining time was reported by Halkaci and Erden [3]. But for all these studies, real time experimentation was required which consumes lot of time and resources. So, research works were started to model the EDM process using finite element methods. Bhondwe et al. predicted the material removal rate in EDM process using finite element
formulations [4]. They conducted parametric studies on electrolyte concentration, duty factor and energy partition and they found that increase in all these three parameters increases material removal rate. Numerical modelling of EDM process in thermal aspects was discussed by Vishwakarma et al. [5].

Though finite element modelling of electro discharge machining process has been already done, it was based on thermal aspects only. Also, no emphasis was given to machining time which is one of the most critical issues in recent advancements like micro-EDM. This paper models the process in electrical aspects and estimates process efficiency using numerical models. Process efficiency helps to find out if there is any scope for improvement in process and therefore enhanced productivity. This is similar to a control chart which specifies if a process is in control or not. Though surface finish is the critical factor conventional EDM process, machining time is the most critical factor for recent advancements such as micro-EDM process [6]. Also, manufacture of micro-sized electrodes for research purpose is very difficult. Thus, prediction of machining time using numerical modelling overcomes many constraints in real time experimentation and saves time and resources. Thus, the objective of this paper was to define coefficient of erosion and prove it to be constant analytically and validate experimentally. Using this constant, electro-discharge machining process was numerically modelled using moving mesh feature in a commercial finite element analysis package. Software modelling was demonstrated by estimating process efficiency of a drilling process and its relation with productivity was studied. In order to justify the application of software modelling for research, concentric electrodes and conductivity enhancement rings were defined and compared with conventional micro-EDM process with the respect to machining time.

2. Analytical method

Erosion coefficient is defined as the volume of material removed (V1) for given value of supply current (I) and given time of passage of current (t) in EDM process. This term has got several definitions in different areas. For example, thermally it is referred as coefficient of boiling and can be defined as the displacement of material removed for given value of temperature and time of exposure to that temperature as explained by Manfred Lindmayer [7]. In this analysis, former definition is considered. Thus, erosion coefficient (K) may be represented as shown in equation (1).

\[ K = \frac{V_1}{It} \]  

(1)

It is assumed to be constant for a particular material and the theoretical background for erosion coefficient being constant for a particular material is explained as follows. The amount of heat generated (Q) due to passage of current (I) and resistance (R) are given in equation (2) and (3).

\[ Q = I^2Rt \]  

(2)

\[ R = \rho L/A \]  

(3)

Since length (L) and area (A) are constant, resistance (R) depends on specific resistivity of a material (\( \rho \)) which is constant for a particular material. The volume of material removed depends on the temperature generated due to the spark at the surface of the component. When the temperature exceeds vaporization temperature of the component to be machined, material gets removed from the surface. The rate of erosion is constant for particular material and is proportional to difference of arc temperature and vaporization temperature of the component. Thus rate of erosion depends on the arc temperature which in turn depends on the current, resistivity of material and time of passage of current. This supports the definition of erosion coefficient.

When electrodes are brought in contact with the component and retracted, a molten crater is formed due to heat generated by the supply current due to ionisation of air gap. It is assumed to be hemispherical with radius (r). The material is removed for every pulse from the work piece. The actual time of machining is the pulse on time denoted by \( T_{on} \). The time where the molten material is flushed away during no pulse is considered to be pulse off time denoted by \( T_{off} \). One cycle time is the combination of a pulse on time and a pulse off time. Harpeet Singh [8] explained the influence of pulse time on material removal rate. They concluded that increase in pulse off time always increased material removal rate. Gostomirovic [9] found that increase in pulse parameters increased tool
wear ratio. Thus for single spark, a hemispherical volume of material is removed in one cycle time ($t_c$). Thus, if total volume of material is removed with $N$ number of sparks, then the product of number of sparks and cycle time would be the time of machining of that particular component.

Let unit hemispherical volume of material be denoted as $\mu$. Thus, total volume ($V_s$) and total cycle time ($T_c$) of material may be calculated as shown in equation (4) and (5).

\[ V_s = \mu N = N\frac{2\pi r^3}{3} \]  
\[ T_c = N t_c = (T_{on} + T_{off})N \]

Equation (6) shows the energy required to remove unit volume of material ($E_s$). Also, this energy is directly proportional to unit volume of material removed as shown in equation (7). Thus proportionality constant ($M$) would be introduced. Material removal rate (MRR) is defined as the volume of material removed for unit cycle time. Daniel et al. [10] proposed a strategic approach to improve machining rate using finite element analysis aided by ultrasonic. In general, MRR may be related to pulse parameters as shown in equation (8).

\[ MRR = \mu t_c = \frac{E_s}{M t_c} = \frac{VIT_{on}}{M(T_{on} + T_{off})} = V\omega/M \]  

$V$ is the potential developed at the component surface and $I$ is the supply current. Pulse ratio ($\omega$) is set in the machine depending on surface finish requirements. It is a measure of actual machining time of component excluding idle time. The coefficient of erosion ($K$) explained in this analysis is ratio of material removal rate and peak current as represented in equation (9).

\[ K = \frac{MRR}{I} = \frac{V\omega}{M} \]

The potential developed at the surface is a constant as it depends on the resistivity of the material subjected to machining and supply current. $M$ is already defined as a constant in the earlier part of the discussion. Pulse ratio is the parameter set and hence it must be a constant. Thus, coefficient of erosion must be a constant.

3. Experimental Validation

In order to validate whether the erosion coefficient is constant or not, three mild steel plates with repeated dimensions were considered for study. Though there are variants in Electric Discharge Machine (EDM) as discussed by Anand Pandey [11], the experiments for this analysis were carried out using an Die-sinker EDM (Make: Mitsubishi EA8 model). A copper electrode with 8mm by 4mm was used to produce spark and depth of cut was set to be 1mm. Initially weight ($W_1$) of the three plates was measured with a precision of 0.001 g. Process parameters such as peak current and spark gap play a major role in determining the MRR for the component as discussed by Vishwakarma et al. [12]. Peak current was set to 8.6 A. The machine capability was set to normal finish mode. Di-electric medium used for the study was kerosene. The time of passage of current ($t$) for machining to required depth were noted for three cases separately. It was calculated by the product of total cycle time ($T_c$) and pulse ratio. Single pause with constant pulse ratio was set in the machine. After machining, the weights ($W_2$) of the plates were measured again and the erosion coefficient was calculated as shown in Table 1.

Table 1 Calculation of erosion coefficient
As shown in the Table 1, volume of material removed ($\Delta V$) was calculated by dividing difference in weights ($\Delta W$) by density ($\rho$) of material. Then erosion coefficient was calculated by dividing eroded volume by current and time of passage of current. It was inferred that erosion coefficient must be a constant for a particular material. Thus the mean value of erosion coefficient was estimated to be $1.2e-11$ m$^3$/As. The experimental setup is shown in Fig. 1.

![Experimentation for coefficient of erosion using Mitsubishi EA8 EDM](image)

### Table 1

| S.No. | $W_1$ (g) | $W_2$ (g) | $\Delta W$ (g) | $\Delta V$ (m$^3$) | $I$ (A) | $T_c$ (s) | $\Omega$ | $T$ (s) | $K = \Delta V/It$ (m$^3$/As) |
|-------|-----------|-----------|----------------|-------------------|-------|-----------|-------|-------|--------------------------|
| 1     | 113.7949  | 113.607   | 0.1879         | 2.394e-8          | 8.6   | 351       | 0.67  | 235   | 1.185e-11                 |
| 2     | 112.819   | 112.610   | 0.2084         | 2.654e-8          | 8.6   | 304       | 0.8   | 243   | 1.269e-11                 |
| 3     | 108.076   | 107.882   | 0.1939         | 2.470e-8          | 8.6   | 480       | 0.5   | 240   | 1.196e-11                 |

3. **Numerical Modelling**

The next step is to numerically model and analyse the EDM process using a commercial Finite Element Analysis (FEA) package (COMSOL Multiphysics 4.2). One of the unique aspects of this study is the application of moving mesh feature in the field of non-traditional machining. Moving mesh feature is used to simulate the erosion of the top layer of the component due to heat generated due to spark. In conventional finite element analysis, the distribution of the field variable like temperature, pressure, potential etc can be observed in the domain under consideration for given boundary conditions. But this feature allows increase, decrease, removal or expansion of a part of domain under consideration for given boundary conditions. This is achieved by indirectly giving the mesh velocity based on predefined boundary conditions, with which the particular face of the domain should expand or get removed. Initially the component for which experiments were carried out earlier is modelled and imported to this FEA package. The component is modelled as two separate parts and then assembled as shown in Fig. 2. The cavity part is modelled corresponding to the shape of the electrode and it is complementary to the cavity created due to spark machining. This is done to apply moving mesh feature to this part alone which is subjected to erosion. The cavity part is modelled to 8mm by 4mm as per the dimensions of the copper electrode. The depth of the cavity part is arbitrarily set to 3 mm. The depth of the cavity part is simply set by adding a minimum of 2 mm to the machining depth required. The base part is the actual component with machined cavity. This part is modelled to experimental mild steel plate dimensions with a cavity in between to assemble the cavity part with it. In this analysis, the physics under consideration are electric current module and moving mesh feature. Assumptions in modelling are perfectly flat surface, rust free and defect free component. Also, flushing efficiency is 100% and tool
wear is neglected. In moving mesh mode, the domain which will be subjected to erosion i.e., cavity part is chosen. This domain erodes with material removal corresponding to mesh displacements and mesh velocity given to different faces. In this analysis, the top face of the cavity part is given a prescribed mesh velocity in the normal direction as shown in equation (10). It is the rate at which the top face should erode. It depends on coefficient of erosion (K) and current density (J).

\[ U = -KJ \]  

(10)

Fig. 2 Software analysis on EDM (a) Meshed view of the model (b) Displacement due to erosion at 222 s

The value of coefficient of erosion was already estimated from experiment as 1.2e-11 m³/As. It is given as a constant to the software. From experimentatation, the value of current density (J) is calculated from supply current (I = 8.6 A) and area of electrode (A₁ = 32 mm²) as shown in equation (11).

\[ J = \frac{I}{A_1} \]  

(11)

Thus the value of current density (J) is found to be 268750 A/m². Potential (V) given to component surface is estimated from the current density, depth of the plate (L₁ = 10 mm) and electrical conductivity of the material (σ = 0.59e7 S/m) as shown in equation (12).

\[ V = \frac{JL_1}{\sigma} \]  

(12)

Thus, for the given value of current density, the potential generated over plate is calculated to be 0.5466mV. This value is given as input to the top face of cavity part subjected to moving mesh feature. Bottom surface is grounded. Thus the current density supplied during experimentation is fed into software in the form of potential, depth of the component and electrical conductivity of plate. Being a time dependent analysis, time of the passage of current from experimentation was fed into the software. The ultimate objective of this modelling is to apply the same experimental conditions to software and compare the results by analysing the depth of erosion in both cases. On solving, the top surface of the cavity part erodes corresponding to input values and the displacement corresponding to removal of material at all time periods in the input range may be found. For 1 mm depth, machining time required is found to be 222 s. The amount of material removed in terms of displacement during 222 s is shown in Fig. 2 (b).

4. Results and discussion

As explained in section 2, 1 mm depth was machined in 240 s experimentally. But in the software, 1 mm depth is machined in 222 s. Thus, there is a good agreement between experimental and software results. The reason for deviation in results is that the software considers rust free and defect free mild steel plate with perfectly flat surface. But the actual plate considered for study posses a roughness value, has rust formation and defects. Rust formation decreases the conductivity of the plate. Defects such as blow holes provide insulation and affects overall
machining time of the process. Thus, the deviation in result is the indication of the high roughness value of the component surface, defects or rust formation in the plate considered for the study. Also, flushing efficiency is assumed to be 100% and tool wear is neglected in software.

5. Demonstration for applicability of software

5.1 Estimation of process efficiency for drilling process

The next step is to analyse the applicability of software in EDM process by considering drilling process. For this study, a mild steel stepped block in which a hole of diameter 7 mm is to be drilled to a depth of 2 mm, is considered. It is modelled as two separate parts namely, cylindrical cavity part and base part as shown in Fig 3 (a). Giving these inputs to software, it is found that 2 mm depth could be machined in 905 s with a pulse ratio of 1 (no idle time). To calculate actual machining time with practical value of pulse ratio (say 0.6), software time is divided by pulse ratio and it is found to be 1810 s. The eroded model is shown in Fig 3 (b).

![Fig. 3 Software analysis on drilling (a) Meshed view of component (b) Displacement (2 mm) due to erosion of material](image)

As explained in section 3, the main assumptions of the software are perfectly flat surface, rust free and defect free component. Also, flushing efficiency is 100% and tool wear is neglected. But, in real practise, all these factors affect the machining time and finish of the component. Tool wear is one of the critical issues affecting the EDM performance parameters [13]. Thus, the lowest possible machining time with which the hole can be drilled using EDM process with perfect conditions can be found using software.

If the actual machining time for drilling the step block as explained in the earlier part of this section is assumed to be 1890 s for pulse ratio of 0.6, the process efficiency is calculated as 95.71 %. Thus, for every machining process, the component could be modelled and analysed in software and then process efficiency of the actual process can be estimated. This is similar to that of a control chart which determines if a process is in control or not. A target value of process efficiency can be set and the process parameters are improved to achieve this target and improve the overall productivity of the process. When the machining of mild steel plate in section 3 is considered, the deviation of 7.5 % may be due to irregular surface of the component, rust formation, presence of blow holes, practical flushing efficiency or tool wear. When these parameters are improved, efficiency may increase. This implies that the actual machining time is reduced and overall productivity of the process is improved. But in order to improve process efficiency, top surface of the component must be polished to have negligible roughness value. All the components must be subjected to thorough inspection with advanced techniques to avoid defective components. Also, the component surface must be chemically treated to avoid rust formation at the time of stocking. Electrodes with least tool wear must be used. Perfect spark gap control must be achieved using precise servo mechanism. Flushing rate must be as high as possible. In order to achieve high flushing efficiency in drilling process, electrode rotates while drilling [14]. It was found that both material removal rate and electrode wear rate increased with the usage of rotating electrode. All these conditions require high operating cost. Thus, a proper balance must be achieved between operating cost and process efficiency. This
balance may be achieved by optimization of these operating parameters.

5.2 Batch mode micro-EDM

One of the potential applications of this software modelling is the prediction of machining time in micro-EDM process. Among the variants of EDM, machining time is a critical issue in micro-EDM [6]. As manufacture of micro size electrodes are very difficult for research purpose, software prediction of machining time is a better option to save time and resources. The current research focussing on batch mode micro-EDM process is considered for this study. Batch mode micro-EDM [15] is a special type of micro-EDM in which multiple micro holes and cavities with same dimensions are machined simultaneously in a component using multiple electrodes. These multiple electrodes attached to a single pallet is called electrode array and there is uniform supply of current to all the electrodes. The position of these electrodes in the pallet corresponds to position of micro holes in the component. This method of micro machining is generally employed to reduce machining time and therefore overall productivity of the process. In the research reported [15], it was concluded that the increase in RC (Resistance and Capacitance) pairs connected to multiple electrodes increase machining rate and roughness.

5.2.1 Conductivity enhancement rings:

This study concerns with the use of conductivity enhancement rings for reducing machining time of the component in batch mode micro-EDM process. These rings with high electrical conductivity are fitted with the component in the air gap while machining in the direction of current. Due to enhanced flow of current in the component by avoiding air gap insulation, machining rate is improved. In this study, a stainless steel integral component with two circular plates and a connecting rod is considered. In one of the circular plates, five holes of 100 microns diameter are to be machined to a depth of 150 microns. Similar to numerical modelling in section 5.1, base part with five holes and five cylindrical cavity parts are modelled separately and assembled. Moving mesh feature is assigned to five cavity parts. Since micro-EDM process involves precise machining of components, coefficient of erosion for stainless steel must be calculated from experiments separately as explained in section 3. From the literature survey [15], coefficient of erosion (K) for stainless steel is calculated to be 2.93e-14 m³/As as shown in equation (13) and assumed to be constant for this study. Supply current is set to very low value (0.45 A) for precise machining. Potential applied over the surface is calculated as shown in equation (12).

\[ K = \frac{\text{depth of machining} \times \text{Area of electrode}}{\text{peak current} \times \text{machining time}} \]  \hspace{1cm} (13)

Results of this analysis shows that five holes are drilled in 133 s with a pulse ratio of 1 in single pause mode as shown in Fig. 4 (a). For practical value of pulse ratio (say 0.8), machining time is predicted to be 167 s. A silver conductivity ring is fitted in the air gap between two discs. Similar analysis shows that machining time reduced to 60 s (nearly half) due to enhanced flow current with less air resistance as shown in Fig. 4 (b). For practical pulse ratio (say 0.8), machining time is predicted to be 75 s. But, only when these rings are fitted in the direction of current, they enhance flow of current and hence reduce machining time by avoiding insulation. Thus, software analysis shows that conductivity enhancement rings improves machining rate.
5.3 Micro size concentric electrodes

The same procedure can be applied to conventional micro-EDM process. Yet another comparison study is performed to predict and compare machining time for producing micro size concentric holes using conventional and concentric electrodes in a stainless steel plate of 3mm diameter and 1 mm depth. Conventionally, concentric holes with two diameters D₁ and D₂ to depths L₁ and L₂ (with reference to top surface) respectively are drilled in two stages. They are drilled with two conventional electrodes of diameter D₁ and D₂. But it is very difficult to maintain concentricity of the two holes as they are drilled using two separate electrodes. Thus, concentric electrodes are defined to drill both the holes in single stage itself. These integral electrodes contain rods of diameter D₁ and D₂ to depths L₁ and L₂ respectively. Initially, electrode rod with diameter D₁ is exposed to component surface and hole with diameter D₁ is machined to a depth of L₁-L₂. After this depth, rod with diameter D₂ is also exposed to component surface in addition to rod with diameter D₁, and thus, hole with diameter D₂ is machined to depth L₂ simultaneously. The holes formed are perfectly concentric to each other as they are machined using same electrode. But the manufacture of micro size concentric electrode for real time experimentation is very difficult and hence software prediction proves to be a better platform for research. For this study, concentric holes of diameter 200 and 100 microns are to be drilled to a depth of 500 microns and 1 mm (with reference to top surface) respectively. Machining time is to be predicted for conventional electrode and concentric electrode and results are compared. Machining with conventional electrode is modelled in two steps similar to real time machining. In the first step, machining time for drilling inner hole of diameter 0.1 mm to depth 1 mm is predicted to be 535 s as explained in section 5.1. Followed by this, component with inner hole machined in the first step, is modelled again and the machining time for drilling outer concentric hole of diameter of 0.2 mm to depth 0.5 mm is predicted to be 665 s. Thus, total machining time of drilling this concentric hole in two stages is predicted to 1200 s. Then, machining time is predicted for drilling concentric holes with concentric electrodes. As explained in section 5.1, concentric cavity part and base part with complementary concentric holes are modelled and assembled. Fixed parameters such as electrical conductivity and coefficient of erosion of stainless steel are given as input. Moving mesh feature is assigned to cylindrical cavity part. Current density distribution and potential applied over surface are calculated from area of electrode (A) and peak current (0.45 amp) as shown in equation (11) and (12). Since area of the concentric electrode in contact (A) varies with depth, it is calculated for concentric holes of diameter D₁ and D₂ to depth of L₁ and L₂ respectively as shown in equation (14).

\[ A = \frac{\pi (D_1^2 \cdot L_1 + D_2^2 \cdot L_2)}{4 \cdot (L_1 + L_2)} \]  

(14)

Results of the analysis infer that concentric holes are machined in 1140 s as shown in Fig. 5. Software results infer that machining time is greatly reduced with the use of concentric electrodes. Also, problem of maintaining concentricity of holes is greatly reduced with the use of concentric electrodes. Thus, this analysis helps to predict and compare machining time for drilling micro size concentric holes using conventional and concentric electrodes without the need for real time machining.
6. Conclusion

The coefficient of erosion was defined and found to be constant for a particular material using experiments in EDM process. There was good agreement between experimental and software results with a deviation error. Though a number of research works were conducted for simulating electric discharge machining, they were based on thermal models using Joule effect as explained by Pradhan [16] and Marafona [17]. But, this work modelled electric discharge machining in electrical aspects. The application of software simulation was demonstrated by predicting machining time for drilling a hole to required depth for given boundary conditions. As the software assumes perfectly flat surface, rust free surface, defect free component, 100% flushing efficiency, no tool wear, perfect pulse timing and perfect spark gap control, software simulation may be considered as a benchmark and thus used to estimate process efficiency. In industries, this software simulation could be used to improve productivity of the EDM process with the aid of process efficiency. One of the recent advancements in EDM is the micro-EDM process where micro holes are machined using sparks was considered for study. Machining time was predicted and this greatly reduces time and resources for research. Machining time for conventional and concentric electrode is predicted and compared. Also, conductivity enhancement rings were defined and their effect on machining time was studied. As the real time manufacture of micro sized electrodes are very difficult, research activities using software proves to be a better platform.

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