Application of MCDM Methodology for Performance Evaluation of Inkjet Based Micro-Fabrication Process

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Abstract. Recently drop on demand based direct write inkjet printing technology has been used in application areas like printed electronics, sensor fabrication in micro-nano scale. It also finds its employability in micro fluidics and drug development application as a micro scale dispensing medium. Like any other real field application problem, E-jet have several criteria or attributes and to fully realise the potential of this technology, fulfilling them is a tricky issue. This paper proposes the application of Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to come up with an alternative which could handle the multi-criteria decision-making problem for E-jet microfabrication process. The proposed methodology has done an exhaustive search among several alternatives in a chosen experimental domain, while tries to strike a trade-off between ejected droplet diameter and throughput of the process simultaneously. After conducting the analysis the favourable operational condition of the process has been identified. The proposed approach can be used as an offline quality improvement measure of the said process.

1. Introduction
With the growing demand for micro- and nano-scale devices in flexible electronics, sensor fabrication and microelectromechanical systems (MEMS) search for new fabrication method has emerged to complement and to meet the challenges faced by conventional fabrication methods. Conventional fabrication technologies such as photolithography, vacuum deposition method suffers from resolution aspect. Inability to handle flexible substrate, the cost associated with very complex post-processing operation, material substrate combination limitation along with material wastage is some of the issues which drive researchers towards direct write printing technologies.

Electrohydrodynamic inkjet or E-jet is a high-resolution patterning technology for microfabrication [1]. Being a non-contacting bottom-up process it can handle very fragile substrate and also able to print on planar or curved substrates, which is essential for flexible electronics purpose [2]. Because of its versatility, it can able to process liquid as well as solid colloidal solutions. It is scalable. So it can be used for large area deposition to dense device integration for the reduced size of the devices. As it is a free form fabrication method and has a potential to be layered manufacturing process [3], material wastage is almost avoided, thus making the process is cost effective. It also has the added feature like the drop on demand functionality, accurate registration ability. Because of the aforementioned advantages, it finds it's applicability in printed electronics [3], bio-sensors [4] and also microfluidic operation.
E-jet printing uses electrical energy for deposition compared to the thermal or piezo-based actuation mechanism for conventional ink-jet technologies [5]. A potential difference is applied between the nozzle containing the conductive ink and the substrate. When the applied potential difference becomes greater than the surface tension of the ink material, the pendant meniscus at the tip of nozzle deformed into a conical shape known as Taylor cone [6] and eventually, ink material gets detach from the tip of the cone. As the material ejects from the cone rather than the nozzle the feature dimension becomes smaller than the nozzle. This is the main reason for its high-resolution operation. Both continuous, as well as discrete features can be generated by this method, as the printing can be done either in continuous mode or drop on demand mode. The following diagram presents various components of the system.

![Diagram of Electrohydrodynamic (EHD) printing system](image)

**Figure 1 Schematic diagram of the Electrohydrodynamic (EHD) printing system**

It involves an ink chamber, pressure supply system, the nozzle as an ejection aperture, voltage system for application of potential difference, substrate on which deposition occurs and the computer controlled stage for moving the substrate to create user-specified geometry. Both AC and DC current supply can be used for the operation.

Over the years researchers tried to explore various aspect of this new emerging fabrication method. Li [7] studied the effect of pulsed voltage on various ejection modes of the material and characterizes the process operation in terms of duty cycle, pulse width. Chen et al. [8] successfully printed sub-micron level droplets in drop on demand mode, thus eliminating of manufacturing very small size nozzles to get the high-resolution feature. Scaling laws has also [9,10] been developed by the researchers to give some idea of the relationship between operational variables like jet diameter, the surface tension of the ink material etc. and response variable like ejection frequency. Traditionally the speed of operation of this technology is somewhat lesser than that of conventional peers. Kim et al. [11] try to address the throughput issue associated with this emerging manufacturing technology. They propose a hybrid printing system to ramp up the output. They have used a piezo-based actuation mechanism to get finer droplets. Mishra et al. [12] achieve printing output of KHz range using pulsed input voltage. They also presented independent control of droplet size and frequency. Park et al. [13] developed a methodology to predict the droplet diameter and compare them with experimental results, thus improving the controllability of the process. Yu et al. [14] try to optimize the process in terms of ink’s viscoelastic behavior. They developed two separate model one each for elasticity and viscosity. Apart from that, there are other works [15, 16, 17] devoted to studying the effect of physical properties of ink material like surface tension, conductivity etc.

After carefully going through the literature, no systematic study has been found to mitigate the decision-making problem associated with this process i.e. tradeoff between two conflicting decision criteria. The goal is to minimize the droplet size for better resolution operation at the same time enhance the ejection rate of the process to make it more robust. Thus the present problem can be viewed as a multi-criteria decision-making problem (MCDM) involving two attributes. Some initial
study has been [18] carried out for performance evaluation of E-jet process. Proper implementation of MCDM technique to investigate the complex E-jet process can give some useful insights about the process, which can be used for better control of the system. From, the decision maker’s point of view, an alternative should be selected from the pool of alternatives so that multiple criteria or design attributes satisfied simultaneously. However, there is no such study found in the literature. This motivates the present work. An attempt has been made to implement a MCDM methodology for predicting the most favorable operating condition of E-jet process through a case study. Traditionally MCDM techniques have been employed quite successfully in such scenarios where multiple attributes or quality characteristics have to be satisfied with a reasonable trade-off [19-21]. Most of the real-field application process or a product involves multiple criteria, many of them may be conflicting in nature also. In such scenarios, decision making process becomes very difficult. An alternative may work for one response variable but it may have an adverse effect on other response variables. From a process engineer’s perspective, there should be one alternative which could satisfy the responses in an optimum way. MCDM techniques work quite satisfactorily in this regard [22, 23]. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is one of the MCDM technique available in the literature. Successful applications of this MCDM technique has been found in the literature [24, 25]. Present work tries to apply Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) approach, to select an alternative which serves the purpose favorably. TOPSIS [26] is an MCDM technique, used to suggest the best alternative among the available ones, to achieve a decision which serves the objective a satisfactory way.

The rest of the paper is organized as follows: section 2 provides a brief description of the methodology, section 3 deals with observation and analysis, section 4 discusses the key findings of the study. And lastly, section 5 provides some concluding remarks and future directions.

2. Proposed Methodology
This work deals with the application of TOPSIS, in E-jet fabrication process to predict the process operation condition which leads to desirable results. There is a vast literature [27, 28] available how this technique has been used in many manufacturing scenarios to promote better process control. It is a simple ranking method which tries to choose alternatives so that it can simultaneously improve the effect of beneficial criteria and dampens the influence of non-beneficial ones. It attempts to select a solution which is closer to a positive ideal solution and at the same time far away from the negative ideal solution. There are several steps involved while conducting TOPSIS, these are given below [29]

- Forming an initial decision matrix. This is mainly composed of the attribute’s value i.e. responses corresponding to available alternative i.e. chosen parameter setting.
- Construction of the normalized decision matrix using the values of the previous decision matrix.
- Formulation of weighted normalized decision matrix after selecting the appropriate priori weights of each attribute or response. This is done to give relative importance to the individual responses.
- Evaluating ideal positive and negative solutions.
- Determining the separation measures for each alternative or observation using ideal solutions.
- Computation of the relative closeness coefficient and ranking of the alternatives based on closeness coefficient values.

The required formulas [27, 28] for performing the aforementioned steps are given elsewhere and cannot be included here because of the space limitation.

3. Observation and Analysis
In the present study, experimental data has been collected from the previous parametric studies conducted by Graph [30]. The input variables chosen for investigation were applied pressure at the ink chamber, the standoff height between the nozzle and the substrate, and the applied voltage. Droplet deposition frequency and the droplet diameter selected as the response of the process. According to the
experimental layout, eight experiments were conducted to study the parametric region. The experimental layout is a two-level fractional factorial design. Two levels of each factor have been investigated. The setting of standoff height includes 30 µm to 50 µm; those of applied back pressure include .25 psi to 1psi and the applied voltage was set of two values high and low. The ink material used for printing operation was Norland Optical Adhesive (NOA) a clear colorless liquid photopolymer, which finds its application in printed electronic industry for bonding purpose. The particle analysis gave the average droplet diameter. Image J software has been employed for particle analysis. For calculating average droplet frequency, stage speed for each run and the travel distance of droplets has been used. The goal of the methodology is to maximize the deposition rate and minimize the feature resolution.

The observed experimental investigation values are presented in Table 1. This table serves as an initial decision matrix.

### Table 1. Control variables & response variables [30]

| Exp. No. | Pres. (psi) | Gap (µm) | Volt. (V) | Ave. Drop Freq. (Hz) |
|----------|-------------|-----------|-----------|----------------------|
| 1        | 0.25        | 30        | Low       | 50.88                |
| 2        | 0.25        | 30        | High      | 383.6                |
| 3        | 0.25        | 50        | Low       | 74.08                |
| 4        | 0.25        | 50        | High      | 326.6                |
| 5        | 1           | 30        | Low       | 83.38                |
| 6        | 1           | 30        | High      | 285.1                |
| 7        | 1           | 50        | Low       | 39.77                |
| 8        | 1           | 50        | High      | 253.1                |

### 3.1. TOPSIS

The initial decision matrix is the order of m*n, m is the no. of alternatives and n is the no. of criteria or attributes. In this study m=8 and n=2. After constructing the initial decision matrix, normalized matrix has been formulated. Table 2 shows the normalized matrix.

### Table 2. Normalized Matrix

$$R_{p} = \begin{bmatrix} 0.079 & 0.324 \\
0.595 & 0.412 \\
0.115 & 0.263 \\
0.507 & 0.430 \\
0.129 & 0.356 \\
0.442 & 0.292 \\
0.062 & 0.436 \\
0.393 & 0.265 \end{bmatrix}$$

### Table 3. Weighted Normalized Matrix

$$V = \begin{bmatrix} 0.039 & 0.162 \\
0.297 & 0.206 \\
0.057 & 0.131 \\
0.253 & 0.215 \\
0.065 & 0.178 \\
0.221 & 0.146 \\
0.031 & 0.218 \\
0.196 & 0.132 \end{bmatrix}$$

As mentioned earlier each element of the normalized matrix has to be multiplied by the associated weight values of individual responses to get the weighted normalized matrix. In this study as both the criteria such as deposition rate as well as size equally important, equal weight values (.50) has been assigned. Table 3 gives the weighted normalized matrix.

From weighted matrix, best and worst solution for both the responses has been obtained. Here the criteria for deposition frequency is high and for size is low. Table 4 represents the ideal situation.
Table 4. Ideal solution.

| Attribute     | Ideal positive solution | Ideal negative solution |
|---------------|-------------------------|-------------------------|
| Deposition rate | 0.297                   | 0.031                   |
| Droplet size  | 0.131                   | 0.218                   |

For separation measures, ideal solution value and actual weighted normalized values have been used. The last step of this analysis is to determine the relative closeness of the alternatives. The favorable condition and ultimately decision should be taken on the basis of closeness value. The following table depicts the last step of the analysis.

Table 5. Separation measure and relative closeness value.

| Exp. No. | Separation Measure from ideal solution | Relative Closeness Value (C) | Rank |
|----------|----------------------------------------|------------------------------|------|
|          | Positive (S+)                         | Negative (S-)                |      |
| 1        | 0.259                                  | 0.057                        | 0.179| 7   |
| 2        | 0.075                                  | 0.267                        | 0.781| 1   |
| 3        | 0.240                                  | 0.091                        | 0.275| 5   |
| 4        | 0.095                                  | 0.222                        | 0.702| 3   |
| 5        | 0.237                                  | 0.052                        | 0.181| 6   |
| 6        | 0.077                                  | 0.203                        | 0.724| 2   |
| 7        | 0.280                                  | 0.000                        | 0.001| 8   |
| 8        | 0.101                                  | 0.186                        | 0.649| 4   |

4. Discussion
Each alternative has been assigned a preference number under the rank column in Table 5 according to their relative closeness value. According to the methodology, this value indicates the proximity of a particular alternative to the ideal case scenario. It can be clearly seen that experiment no. 2 has the highest closeness value and thus assigned rank 1. It means that factor settings at experiment no. 2 have the best potential to give better result among all the other available alternatives. The favorable operational condition relative to the alternative no. 2 are- pressure .025 psi; standoff height 30 µm; and applied voltage is of low level. The present problem has two attributes or criteria and a decision has to be made in such a way that a satisfactory trade-off can be achieved as it is very difficult to find a solution which could satisfy both the attributes fully. And it is quite evident on the observation chart at Table 1. The maximum deposition frequency and minimum droplet diameter achieved in investigated parametric space were 383.6 Hz and 1.32 µm. These values were obtained at different factor settings i.e. at different operating conditions namely at observation no. 2 and observation no. 3 respectively. At observation no. 3 while the resolution is at very high level but achieved deposition rate is very low. Clearly, those factor setting might help to achieve one goal but the other goal is not well taken care of. The proposed alternative according to the methodology has the highest deposition frequency while achieved droplet dimension has a reasonable trade-off also. So the decision-making problem associated with which operational setting gives reasonable outcome has been solved quite effectively.

5. Conclusion
The present work tries to handle a multi-criteria E-jet based micro-fabrication problem. The proposed methodology is based on an MCDM technique called TOPSIS. The methodology suggested an alternative which could strike a balance between two conflicting attributes simultaneously. The most
favorable operational setting of the fabrication process has been reported. The proposed values of applied pressure, nozzle to substrate gap and applied voltage obtained from the analysis are 0.25 psi, 30 µm and high value of applied voltage respectively. The aforesaid process environment could result high deposition rate along with low diameter of ejected droplet simultaneously with reasonable trade-off. The proposed closeness value evaluates and arranged tunable parameters setting in a systematic way for a given printing condition. The report can serve as a template for better control of any production process involving multi-criteria scenario.

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