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OPTIMIZATION OF PROCESS PLANNING FOR FOCUSED ION BEAM MACHINE IN NANO-MANUFACTURING

By

SUSHRUT SHEKAR NAIK

A THESIS

Presented to the Faculty of the Graduate School of the
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In Partial Fulfillment of the Requirements for the Degree

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Approved by

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ABSTRACT

The current revolution witnessed by nanotechnology is facing several challenges such as manufacturing of nano sized devices economically on a large scale. Focused ion beam (FIB) technology is one of the widely used approaches for nano-manufacturing due to its versatile nature. It provides accurate machining and process repeatability and has a range of applications. Major challenges for the current FIB process are the tradeoffs between quality, the processing time, and the long planning time. This research provides a pathway to eliminate the current problems facing nanotechnology. Using MATLAB and the Helios 600 FIB/SEM instrument available, modeling and analyses are carried out to find the optimized process planning for arbitrary 3D nanofeatures.

This research provides information on the current status of the FIB machining process, while at the same time discusses the challenges in FIB manufacturing. It provides a methodology that can be used to achieve an increase in planning and processing efficiency without sacrificing fabrication quality. This is done with the help of an iterative algorithm developed to achieve the optimized solution to a quadratic programming problem. Furthermore, the analyses carried out provides with more information on the choice of the scanning spacing, its corresponding effects on the quality of the product and computational efficiency. This is illustrated with the threshold step size selection and the beam overlap phenomenon. The thesis concludes with the set goal of achieving an increase in the planning and processing efficiency while maintaining the quality. It provides possible future course of actions in the same field, such as the beam flexibility criteria, using the additive process and the serpentine scan for manufacturing.
ACKNOWLEDGMENTS

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Finally, I would like to thank my parents Mr. Shekhar Naik and Dr. Mrs. Pankaja Naik for their unconditional love and support.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>...............................................................</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>...............................................................</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>...............................................................</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>...............................................................</td>
<td>viii</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>...............................................................</td>
<td>ix</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>...............................................................</td>
<td>1</td>
</tr>
<tr>
<td>1.1. NANO-MANUFACTURING</td>
<td>...............................................................</td>
<td>1</td>
</tr>
<tr>
<td>1.2. FOCUSED ION BEAM SYSTEM</td>
<td>...............................................................</td>
<td>4</td>
</tr>
<tr>
<td>1.3. SETUP OF THE FOCUSED ION BEAM SYSTEM</td>
<td>...............................................................</td>
<td>7</td>
</tr>
<tr>
<td>1.3.1. The Liquid Metal Ion Source (LMIS)</td>
<td>...............................................................</td>
<td>7</td>
</tr>
<tr>
<td>1.3.2. The Lens System</td>
<td>...............................................................</td>
<td>8</td>
</tr>
<tr>
<td>1.3.3. The Work Chamber</td>
<td>...............................................................</td>
<td>9</td>
</tr>
<tr>
<td>1.3.4. User Interface</td>
<td>...............................................................</td>
<td>10</td>
</tr>
<tr>
<td>1.4. APPLICATIONS</td>
<td>...............................................................</td>
<td>11</td>
</tr>
<tr>
<td>1.5. CHALLENGES FOR SUCCESSFUL IMPLEMENTATION OF NANO-MANUFACTURING</td>
<td>...............................................................</td>
<td>13</td>
</tr>
<tr>
<td>1.6. RESEARCH STATEMENT</td>
<td>...............................................................</td>
<td>14</td>
</tr>
<tr>
<td>1.7. THESIS OUTLINE</td>
<td>...............................................................</td>
<td>14</td>
</tr>
<tr>
<td>2. LITERATURE REVIEW</td>
<td>...............................................................</td>
<td>16</td>
</tr>
<tr>
<td>2.1. PRINCIPLE OF FOCUSED ION BEAM SYSTEM</td>
<td>...............................................................</td>
<td>16</td>
</tr>
<tr>
<td>2.2. THE CURRENT STATUS IN FOCUSED ION BEAM MACHINING</td>
<td>...............................................................</td>
<td>18</td>
</tr>
<tr>
<td>2.2.1. The Variable Dwell Time Approach</td>
<td>...............................................................</td>
<td>18</td>
</tr>
<tr>
<td>2.2.2. Slice By Slice Cut Approach</td>
<td>...............................................................</td>
<td>27</td>
</tr>
</tbody>
</table>
2.3. CHALLENGES IN FOCUSED ION BEAM MACHINING ......................... 28

3. THE MODEL .................................................................................. 33

3.1. SYSTEM SETTING ........................................................................ 33

3.1.1. The Decision Variable ............................................................... 38

3.1.2. The Constraints ....................................................................... 39

3.1.3. The Objective Function ............................................................ 43

3.1.4. The Mathematical Model .......................................................... 44

3.2. OPTIMIZATION ALGORITHM ..................................................... 45

3.3. SOLUTION .................................................................................. 49

4. RESULTS AND NUMERICAL ANALYSIS .................................... 52

4.1. THE INPUT PARAMETER TABLE ................................................. 52

4.2. EXAMPLE 1 ................................................................................ 53

4.3. EXAMPLE 2 ................................................................................ 63

4.4. SELECTION OF SUITABLE STEP SIZES FOR MACHINING AND DETERMINATION OF THE THRESHOLD STEP SIZE ......................... 66

4.5. SELECTION OF SUITABLE BEAM OVERLAP ............................. 69

4.6. EXPERIMENTAL DESIGN DATA ANALYSIS .............................. 71

5. CONCLUSION ............................................................................... 75

APPENDIX ...................................................................................... 79

BIBLIOGRAPHY .............................................................................. 83

VITA ................................................................................................ 86
# LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1</td>
<td>Nano-Manufacturing Techniques</td>
<td>3</td>
</tr>
<tr>
<td>Figure 1.2</td>
<td>Schematic Representation of 2 Lens FIB System</td>
<td>10</td>
</tr>
<tr>
<td>Figure 1.3</td>
<td>Focused Ion Beam System</td>
<td>11</td>
</tr>
<tr>
<td>Figure 2.1</td>
<td>Principle of Focused Ion Beam System</td>
<td>17</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>Parallelopiped Used For Experimentation</td>
<td>34</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>Scanning Methods</td>
<td>37</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>The Gaussian Distribution</td>
<td>40</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>The Objective Function Plot</td>
<td>55</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Plot Obtained From Actual Machining</td>
<td>56</td>
</tr>
<tr>
<td>Figure 4.3</td>
<td>Corrected Machining</td>
<td>58</td>
</tr>
<tr>
<td>Figure 4.4</td>
<td>Deviation From The Ideal Objective Function (A*t-Z)</td>
<td>59</td>
</tr>
<tr>
<td>Figure 4.5</td>
<td>Total Error At Each Iteration V/s No. Of Iterations</td>
<td>60</td>
</tr>
<tr>
<td>Figure 4.6</td>
<td>Histogram</td>
<td>61</td>
</tr>
<tr>
<td>Figure 4.7</td>
<td>Example 2</td>
<td>64</td>
</tr>
<tr>
<td>Figure 4.8</td>
<td>Step Size V/s Error (Example 1)</td>
<td>67</td>
</tr>
<tr>
<td>Figure 4.9</td>
<td>Step Size V/s Error (Example 1)</td>
<td>68</td>
</tr>
<tr>
<td>Figure 4.10</td>
<td>Beam Overlap</td>
<td>70</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 4.1 The Input Parameters For Helios 600 FIB/SEM ........................................52
Table 4.2 Experimental Results (Spherical Lens) ..........................................................71
Table 4.3 Experimental Results (Uniform Depth Cavity) .............................................73
### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Population mean</td>
</tr>
<tr>
<td>$Y_s$</td>
<td>Erosion rate</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Importance put on the milling cost</td>
</tr>
<tr>
<td>$t_j$</td>
<td>Decision variable (time)</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

1.1. NANO-MANUFACTURING

Nano-manufacturing is described as a term used for manufacturing products which are very small in size (of the order of $10^{-6}$ m to $10^{-9}$ m). Essentially, nano-manufacturing can be described as building nano scaled structures which act as small components, or devices in larger systems (Tseng, 2005). Scientifically, nanotechnology can be defined as the science that captures both the present and future direct control of materials and devices on both the molecular and atomic scale (Chryssolouris et al., 2004). The focused ion beam (FIB) systems can be used to manufacture objects of such small scales, because they have a very short wavelength and possess very high energy density (Tseng, 2004). One of the two basic modes of working of an ion beam is the direct write technique, also known as focused ion beam milling (FIBM). The second mode is the ion beam projection process, also known as focused ion beam lithography (FBIL). FBIL can serve as an alternative method to conventional lithographic processes (Tseng, 2004). The ion projection printing, also known as ion projection lithography (IPL) enables parallel production of a large number of devices and is a major candidate for next-generation lithography (NGL) (Tseng, 2005). The major benefits of nano-manufacturing include minimizing the use of materials and its impact on environment and energy. At the same time, it also increases product resolution and sensitivity (Tseng, 2005).

Nano-manufacturing methods can be broadly classified as either top-down method (TDM) or bottom-up method (BUM). The TDM method can be explained as a procedure of modifying the given material through a man-machine combination. The top-down method was developed by Taniguchi in 1974, and is also known as the transformative approach or
an approach from larger to smaller (Chryssolouris et al., 2004). The modifications applied to achieve machining might include various steps of milling, drilling, etc. to remove material. In short, TDM can be defined as material removal process which can be seen as shown in the Figure 1.1(a). Figure 1.1(a) illustrates how a larger cube of a certain material is converted into smaller cubes by the removal of material in subsequent stages. A log of wood altered to form baseball bats is a classic example of the TDM approach. The top-down approach is widely used as compared to BUM. TDM can be used for controlled fabrication and assembly. However, TDM is not easy to parallelize at small scales when the manufacturing of larger products is performed. However, when we manufacture products of nano meter scale, the drawback of parallel processing is not significant and can be neglected. The entire integrated circuit manufacturing industry bases its thousands of process steps on a top-down model. TDM techniques have been refined to increase the number of individual components on each integrated circuit, with fine refinement in Moore’s Law (Tseng, 2004). The various nanofabrication methods such as focused beam lithography (FIB), the nano-imprint lithography (NIL), electrochemical material removal process, and the ink jet lithography are based on the TDM.

The alternative method to the top down method of manufacturing is the bottom-up method (BUM) discovered by Drexler in 1986. The main idea underlying this approach uses atomic or molecular sized components to build a larger complex structure (Chryssolouris et al., 2004). It is also known as the synthetic approach. The bottom-up method deals with organizing the individual atoms or molecules in a special configuration to form the larger complex product (Chryssolouris et al., 2004). Nano fabrication methods such as contact printing, imprinting, spinodal wetting, laser trapping, and electrostatic coating are some
examples which use the bottom-up method to achieve successful manufacturing (Chryssolouris et al., 2004). One major disadvantage of the bottom-up method is that it can be used only for making complex products which are homogenous in nature. The method fails to produce products which are heterogeneous in nature (Zhang et al., 2003). Heterogeneous in nature means, the final product is composed of two or more materials, which cannot bind together, using the bottom-up method. Efforts are focused on developing a hybrid technique that would incorporate the advantages provided by both TDM and BUM for large scale parallelization (Zhang et al., 2003).

Figure 1.1 Nano-Manufacturing Techniques
(a) TDM (b) BUM
In both the two approaches BUM and TDM, the machining is performed either in a single pass scheme or repetitive pass scheme. For FIB, the number of incident ions per micro square meter of the exposed surface is directly proportional to the material removal rate, with both the current and the incidence angle remaining constant. Milling of various 3D micro and nanostructures have shown that repetitive pass scheme (one in which machining is performed using a low ion density and large number of machining passes) is more beneficial than a single pass scheme (one in which the machining is performed by using a high current density thereby reducing the number of machining passes). This is because, a single pass leads to slant side-walls of the cavity being machined, poor surface quality and a high rate of re-deposition and non-flat bottom surfaces (Koyama et al., 2003). Using a repetitive pass scheme, however, increases both the operating cost and the time required for the production. To ensure an optimum combination of production capacity, it is necessary to devise an optimum process planning strategy for nano-manufacturing. As a rule the place where the depth is more, it is machined at the end of the (machining) process and the place which has a lower depth is machined earlier. This follows an inverse relation that the highest depth cavity is supposed to be machined at the end and the cavity with the lowest depth to be machined first. This is because the re-deposition effects are prominent if the high depth cavity is machined first, leading to a product which does not satisfy the tolerances (Tseng, 2004).

1.2. FOCUSED ION BEAM SYSTEM

Focused ion beam manufacturing, popularly known as FIB manufacturing is a technique that developed in the late 1970s and early 1980’s (Reyntjens & Puers, 2001). Since that time, FIB has found applications in a wide variety of fields such as medical
sciences, engineering (reverse engineering, failure analysis, etc.), physics, image processing, geological sciences, chemistry, and materials (Chrysoyolouris et al., 2004) as well as for pharmaceutical fields (Orloff et al., 2004; Tseng, 2005). It is also used in applications such as modifications of failure analysis of semiconductor devices (Reyntjens & Puers, 2001). The quality of the focused ion beam system of varied applications is attributable to its properties of milling and deposition with high accuracy. It is used in the making of micro and nano sized tools used in the ultra-precision machining process and circuit modification process (Langford et al., 2007; Weiderrecht, 2010). It can also be used in the manufacture of nano-sensors, nano-photonics (Weiderrecht, 2010) in various fields of thermo-fluidic, biochemical, mechanical, electronic, and electric and bio medical applications (Tseng, 2004). The focused ion beam systems can be used to both sputter and implant narrow lines (as small as 10 nm). These systems are also used to deposit metals and insulators in narrow user defined geometries (Langford et al., 2007).

The focused ion beam process can be either a complementary process to some other process for production of micro/nano sized structures, or it can also act as the main production method for micro/nano sized structures. Although focused ion beam methods are advanced, the drawback still remains in the transfer of the technology to widespread industrial applications due to its high operating costs and inefficient application. This upcoming technology for producing nano scaled products has evolved tremendously over the past few years. It has moved far beyond the original perceived application of X-ray and photo-mask repair (Vasile et al., 1999). Extensive efforts into miniaturization have been primarily done to lower the costs by reducing the consumption of other expensive raw materials (Figeys & Pinto, 2000; Tseng, 2005). A classic example of the need for
miniaturization in medical field can be described by the medical assays which once required liters of expensive reagents and solutions that can now be done with the help of a lab-on-chip revolution. Lab on chip is a micro fabricate array used for assays which would reduce the consumption of expensive reagents and solutions by a scale of $10^3 - 10^4$ liters (Figeys & Pinto, 2000). A significant potential lies with the focused ion beam milling process for producing objects in a serial process on a mass scale (Vasile et al., 1999). Micro molds for the mass production of micro objects can be produced by employing an ion milling procedure using a focused ion beam milling machine. The current challenge, however, still lies in controlling the ion dose for milling predefined geometries of the cross sections (Crow et al., 1988).

The focused ion beam machining process also finds its use in the medical field in making micro surgical tool and manipulators. The manipulators processed by the FIB method are used to study the circulatory system of small animals such as mice and rats, whose arterioles and venules are in the micro domain (5 – 15 μm in diameter) (Vasile et al., 1999). These micro surgical tools are very costly due to the fact that these are used for medical purpose and are of small geometry. Hence, their costs can be justified. However, production of micro precision tools used for machining should not have a high cost of manufacturing even if they are manufactured in large or small quantities. Since machining processes are carried out on a larger scale than performing surgical operations, replacement of tools in the machining world is quiet frequent. Hence, the cost should be kept low. This research aids the same ideology of transferring an emerging technology to industry by eliminating the bottleneck of both the efficiency and cost. Amongst the most successful applications of focused ion beam system is the failure analysis. The most outstanding feature
of the focused ion beam systems for all its applications is its flexibility (Reyntjens & Puers, 2001). Thus, it can be seen that the future of nanotechnology will have a profound effect on the societal, economic, ethical, legislative, and everyday aspects of life (Doumanidis, 2001).

1.3. SETUP OF THE FOCUSED ION BEAM SYSTEM

The basic components of a focused ion beam system are an ion source, an ion optics column, a beam deflector, and a substrate stage (work chamber). A workstation which includes the computer/processor provides the user with an interface to work with the system (Tseng, 2005).

1.3.1. The Liquid Metal Ion Source (LMIS). Ions or atoms, which have a deficiency of either one or more orbiting electrons. They have net electrical charges and can therefore be steered with the help of both magnetic and electrical fields (Tseng, 2005).

The liquid metal ion source (LMIS) is housed in the vertical column which is mounted directly over the specimen to be machined or scanned, shown in Figure 1.2. The LMIS typically consists of an extraction electrode, a capillary tube with a needle protruding through it, and a shielding. The capillary tube acts as a storage tank which continuously supplies ions to the tip. Once the ions are at the tip, the ions interact with a strong electrostatic force generated by the extraction electrode and the surface tension causes the liquid metal meniscus to form a cone like shape (known as Taylor Cone) (Tseng, 2004; Koyama et al., 2003). The electric field applied by the electrode causes the positive ions to separate and form a cone at the tip of the needle (Reyntjens & Puers, 2001). The approximate extraction voltage applied to obtain these ions (Ga+) is 7000 V, with a current of 2 μA under normal working conditions (Reyntjens & Puers, 2001). The LMIS was developed in the late 1970 (Reyntjens & Puers, 2001) and is still being used on a wide scale. Various sources used
include As, Ga, He, Zn, P, Pb, Pt, etc. Dopants such as PdAs, PdAsB, AuSi, AuSiBe, etc. can be used for semi-conductor manufacturing (Tseng, 2005). The use of ions depends upon the particular application or process and also on the specimen material properties. Metals which have low melting temperatures and low reactivity can be used as ion sources (Tseng, 2005).

1.3.2. The Lens System. The ion beam is then passed through a mass separator that only allows ions with the required amount of mass to charge ratio to pass through it (Tseng, 2004). The ion beam then passes through a lens system. The lens system eliminates the ions which are not exactly vertical. Next in the path lies the electrostatic beam deflector which controls the trajectory of the beam (Tseng, 2004).

Using a variable aperture mechanism, the beam of various dimensions can be obtained; a fine beam for high resolution sensitive sample imagining and high beam for fast and rough milling (Reyntjens & Puers, 2001). The ion sources developed in this manner are then accelerated to energy of 1-100 keV and focused by using an electrostatic lens system on the specimen being machined or scanned. These ions emitted from the lens system are directed towards the specimen. The substrate gets machined upon the interaction of the ions with atoms of the substrate.
1.3.3. The Work Chamber. Samples which are to be treated by the focused ion beam system are mounted on a motorized table that can be moved or rotated around five axes. It is generally a vacuumized chamber with a pressure of about 10-7 mBar. The loading and unloading of samples is done through a load lock to preserve the vacuum inside the chamber (Reyntjens & Puers, 2001).

A vacuum pump is required to maintain the vacuum inside both the working chamber and the column. The ion column may be provided with an additional pump for pumping the liquid ions through the column. Most focused ion beam systems are equipped with gas cabinets. These gases are used during the machining process to provide a shielding over the surface of the substrate. These gases provide a barrier for any further reaction that may occur during the machining process, which may spoil the surface being machined. These gases also help in faster and selective etching process. These gases flow into the vacuumized chamber through a piping system and are sprayed with the help of a nozzle (Reyntjens & Puers, 2001).

Figure 1.2 represents the schematic diagram of the most widely used two lens focused ion beam system in industrial applications. Figure 1.3 represents the setup of a focused ion beam system with the column which house the LMIS and the lens system. It also displays the work chamber and the monitor and gauges used to control and observe the machining process.
Figure 1.2 Schematic Representation of 2 Lens FIB System
(1) Liquid Metal Ion Source (2) Top Lens (3) Separator (4) Drift Tube (5) Bottom Lens
(6) Beam Deflector & Multichannel Plate (MCP) (7) Nozzle (8) Substrate
Figure taken from "Recent Developments in nanofabrication using focused ion beam," Small (1), No. 10, pp., 924-939; edited by Sushrut Naik on October 30th 2011.

1.3.4. User Interface. The user interface houses all the controls and dials that provide the user with feedback about the on-going machining process in the vacuumized work chamber. It has a micro-processor which controls activities such as the beam current, the aperture diameter, the control for the pumps and gasses, etc. All these activities are aided by a software application (Reyntjens and Puers, 2001).
1.4. APPLICATIONS

The focused ion beam milling process is considered to be a ‘direct write-material removal’ technique in which material is removed from the substrate with the help of an ion beam (Tseng, 2005). The ‘direct write technique’ consists of a collection of several major approaches such as milling, implantation, ion induced deposition, and ion assisted etching (Tseng, 2005). The diameter of the ion beam is varied according to the feature required to be milled and the quality intended (Crow et al., 1988; Yamamura et al., 1983). It is predicted that reverse engineering would also benefit from the advances in the methods of focused ion
beam sculpting (Adams et al., 2006; Vasile et al., 1998). Extensive work at machining rectilinear and curved shapes using focused ion beam has not been carried out, however (Vasile et al., 1988; Vasile et al., 1997; Vasile et al., 1998; Vasile et al., 1999; Fu & Bryan, 2002; Fu et al., 2000). Most of the extensive work has been documented by Vasile (Vasile et al., 1988; Vasile et al., 1997; Vasile et al., 1998; Vasile et al., 1999) and by Fu (Fu & Bryan, 2000; Fu & Bryan, 2002; Fu et al., 2000). The method put forth by Vasile et al. considers the dose of ions required per pixel to obtain the required feature on the substrate. In case of curved features, the method considers both the incidence angle and the variations in the sputter yield caused due to it (removal and re-deposition) (Langford et al., 2007). Another set of work by Vasile et al. considers a mathematical model of focused ion beam sputtering process which provides a variable milling time as output in a deflection pattern for the pre-specified geometry. The outputs provided by this method heavily depend upon the size of the pixel in the deflection pattern, the ion beam dimensions, the sputter yield and the angle of incidence (Vasile et al., 1999).

The work by Fu et al. demonstrates the use of the focused ion beam process for fabricating geometrically complex shapes in a selected few materials. This group demonstrates focused ion beam using micro lens components and diffractive optical elements. A focused ion beam system has excellent source stability and at the same time an ability to reproduce the same feature repeatedly with both high accuracy and efficiency. This makes it appropriately suitable for applications where micro scaled features are necessary. In practice, beam overlap is necessary for a focused ion beam system. Negative overlap means there is a space between adjacent pixels being scanned by the beam. Positive overlap means that the ion beam removes material from adjacent pixels also (Fu et al., 2000).
The focused ion beam process would be very versatile and sophisticated with the addition of a depth control feature by varying the input parameters for the machine. As the dimensions of the structures under consideration decreases the need to understand its mechanical and chemical properties also increases. The process of understanding these properties also gets more difficult due to the complex and small grain structure of the material (Langford et al., 2007). It can complement with other direct write techniques such as micro drilling or X-ray lithography to produce next generation molds and masks for micro-electro mechanical systems (MEMS) (Crow et al., 1988; Reyntjens & Puers, 2001).

The use categorizes the focused ion beam systems into two categories. The first category is the modification or fabrication of structures or geometries that are difficult to manufacture by using traditional or conventional methods. This is mainly because of the material properties or the geometric constraints. The second category includes the rapid prototyping or modification of structures or devices which can be accomplished in fewer, quicker and simpler steps and time, as compared to the conventional process of machining (Langford et al., 2007).

1.5. CHALLENGES FOR SUCCESSFUL IMPLEMENTATION OF NANO-MANUFACTURING

It can thus be said from the previous methods reviewed within this literature, that all have certain drawbacks and lack flexibility. These studies which have been carried out have mostly concentrated on increasing the processing efficiency that is, reducing the processing time required for fabricating each feature on the substrate. This reduction would lead to an increase in the output, for the same proportion of input resources. These studies, however, found that the quality of the feature produced does not match the same quality as that of the
ideal machined feature. Other studies conducted have specifically tried to concentrate on the quality of the feature produced neglecting the processing efficiency. These methods lacked flexibility and did not concentrate on more than one objective at a time. The Centre for Scalable and Integrated Nano-Manufacturing (SINAM) also identifies that the challenges for nano-manufacturing are accuracy and speed of alignment and motion (Zhang et al., 2003).

1.6. RESEARCH STATEMENT

Hence, the problem statement aims at increasing the processing efficiency, maintaining the quality and reducing the costs. The research follows a more algorithmic approach and aims at fulfilling both the objectives of reducing processing time and planning time (increasing processing efficiency) and also maintaining the quality of the product within tolerable range. The proposed method aims at eliminating the drawbacks of the trial and error method currently being employed and fueling the large scale setup for nanotechnology by commercialization. The research will also eliminate the bottleneck of high operating costs of such an innovative technology. Understanding the associated cost with machining for such small scaled features is also important. Although the feature size produced is either in the atomic or the molecular range, the cost associated to produce them is very high. Small scale production of these nano sized particles sometimes even increases the overall cost of production. In order to consider the cost of machining, the cost factor is included within the objective function.

1.7. THESIS OUTLINE

Section 1 provides an introduction to the entire research carried out. In addition, this chapter provides a concise description of terms such as nano-manufacturing. The chapter
discusses the setup of the focused ion beam system, its applications, the present challenges, and a thesis outline.

Section 2 includes the literature review. This literature review summarizes the various experiments carried out to date with focused ion beam systems in nano-manufacturing. The variable pixel dwell time approach by Vasile et al., and the slice by slice cut approach by Fu et al. are described. Other system parameters are also described. It summarizes the iterative approach for quadratic programming.

Section 3 includes the study of the initial model, the decision variables, the constraints, and the objective function. This chapter also includes the discussion on optimization methodology and the solution and at the same time providing explanation of the different algorithms that can be used for the iterative process.

Section 4 explains and discusses the results obtained for the specific beam setting. It considers an example setting and discusses the important effects of parameters that affect the machining process. It also provides information about the input parameters which are machine specific.

Section 5 provides the concluding remarks and how the proposed method could revolutionize the nano-manufacturing field. It points out the important effects of the step-size selection, beam overlap, and the threshold step size. It summarizes the observations made from the numerical analysis performed. It also provides possible suggestions for future course of action.
2. LITERATURE REVIEW

2.1. PRINCIPLE OF FOCUSED ION BEAM SYSTEM

The focused ion beam systems work on a similar platform as the scanning electron microscope (Reyntjens & Puers, 2001). The only distinctive difference between the two operating systems is that the focused ion beam uses the liquid metals as ion source, whereas the scanning electron microscope uses electrons in the operation. The ion beam directed towards the specimen from the focused ion beam system hits the sample surface and sputters small amount of atoms from the substrate (Reyntjens & Puers, 2001). This is illustrated by the Figure 2.1, shown below. Some of the incident ions bounce back from the surface as they cannot overcome the binding energy of the atoms of the substrate (Tseng, 2004). These ions bouncing back are converted into positive or negative ions (+,-), or in some cases they even become neutral ions (n^0) (Reyntjens & Puers, 2001). They are known as secondary ions. The beam of primary ions also has small proportions of secondary ions. These secondary ions can be used in an ion mass spectroscopy of the target material in a mass spectrometer that can be attached to the system (Reyntjens & Puers, 2001). These secondary ions are collected by a receiver to produce an image of secondary ions. This image is then referred to during the machining process to observe the process and the features being produced simultaneously. The amount of material removed directly depends upon the primary beam current. The higher the primary beam current, the higher the amount of material that is removed, and with low beam current the material removed is less. Figure 2.1 represents the principle of working of a focused ion beam system.
The above method holds true for objects which are both good conductors of heat and electricity. If the sample is a bad conductor then an electron flood gun is used to charge neutralization (Reyntjens & Puers, 2001). However, non-conducting materials can be used for inspection without any special treatment in case of focused ion beam systems (Reyntjens & Puers, 2001). The high energy ions used in focused ion beam systems tend to enter the sample surface leading to an adulteration of the original specimen properties (Reyntjens & Puers, 2001). This is known as implantation. Implantation depends upon the angle of incidence and ion energy (Reyntjens & Puers, 2001). This provides an advantage over the scanning electron microscope method which cannot be used for insulating samples. The latest FIB systems available in the market today are equipped with high resolution imaging capability; this capability coupled with in situ sectioning has eliminated the need, in many cases, to examine FIB sectioned specimens in a separate SEM instrument. SEM imaging,
however, is still required for producing images of higher resolution and at the same time to prevent damage to sensitive samples. Hence, the combination of SEM and FIB columns onto the same system would provide us with advantages of both the systems and minimize their drawbacks. Drawbacks such as the chemical interactions such as breaking of bonds or dissociation of molecule, deposition effects taking place can be minimized. This is due to the high energy of the incident ions (Reyntjens & Puers, 2001). Focused ion beam systems can be used for mask-less deposition of both metals and insulator materials. Deposition as small as 100 nm (lateral dimension) and 10 nm (thick) can be done using focused ion beam systems (Reyntjens & Puers, 2001; Tseng, 2005).

2.2. THE CURRENT STATUS IN FOCUSED ION BEAM MACHINING

2.2.1. The Variable Dwell Time Approach. The main reason why ion beam is preferred over electron beam in machining is because of their shorter wavelength and also because of their high energy density (Tseng, 2005). The other reason for the use of an ion beam is that the ions are larger than electrons. Because of this, they cannot penetrate easily within the individual substrate atoms, leading to breaking of chemical bonds only (Tseng, 2004). Due to their heaviness as compared to the electrons they have a higher momentum (Tseng, 2005).

Also, the electron or the photon beam can be used with soft materials such as polymers or resists, and the corresponding feature size is determined by the back scattering of electrons or wave diffraction limits (Tseng, 2005). The feature characteristics, in case of an ion beam depend upon the beam size and interaction with the target material (Tseng, 2005). For an optimized machining process, the ion beam energy is set in the range of 10-100keV (Tseng, 2004), when the current varies from 1 nA to approximately 30 nA.
(Reyntjens & Puers, 2001). For ion beams with energy higher than 100kEV, implantation of the ions occurs within the substrate. While back scattering and nuclear reactions take place for ion beam with energy higher than 1MeV (Tseng, 2004). Depending upon the ion energy, the interaction between the ions and the substrate can be termed as swelling, deposition, sputtering, re-deposition, implantation, back scattering, or nuclear reaction. The various types of metal ions source that are used in the focused ion beam systems include Al, As, Au, B, Be, Cu, Ga, Fe, H, In, Li, Ni, P, Pb, Pt, Si, and Zn.

The focused ion beam machines have been employed for the past two decades commercially especially by the large semi-conductor manufacturing industries. The focused ion beam systems work in a similar fashion as the scanning electron microscope (SEM). The only difference between the functioning being that SEM uses electrons to scan the surface, whereas the focused ion beam system uses a beam of Ga / He ions to scan the object (Introduction: Focused ion beam systems, accessed on November 21st 2011). The diameter of the ion beam used for machining bears a direct relation with the intensity of the current. As the current increases, the diameter increases displaying a direct proportion between the two. A larger amount of material is sputtered with high current. Low current yields low sputter. The work done by Vasile and Adams (2006) demonstrates accurate focused ion beam sculpting of micron scale curved shapes. Sculpting/machining is accomplished by varying the ion dose per pixel and also by varying the pixel dwell time. The entire process is completed by boustrophedonic scanning of the object (Adams and Vasile, 2006). They displayed that the material removed per pixel in a given scan is proportional to the ion dose per pixel and also the time of dwell at each pixel. When both the ion dose per pixel and the incident angle are kept constant and the dwell time range is kept low then, the depth
produced at the respective pixel is less. When the dwell time range is high at a respective pixel keeping both the ion dose and the incident angle constant then, the depth produced is of high order. Milling outside targeted areas takes place when the ion beam scan traces a rectilinear path for features such as a circle, ellipse, or hemisphere.

Vasile et al. used a method based on a mathematical model which uses the combined effects of beam deflection and sputter removal process. In the previous attempts by Vasile et al.; the feature was milled on the substrate using a direct write technique (Vasile et al., 1988; Vasile et al., 1997; Vasile et al., 1998; Vasile et al., 1999; 9). Direct-write fabrication process is a novel technique in which, a focused electron beam or ion-beam is scanned over the sample in the presence of a precursor gas (Tseng, 2005), causing the metals or insulators to be deposited directly onto the sample and with nano meter resolution. The area to be milled is first outlined by an operator and it is then divided into an array of pixels. Next, the cross section is defined and then the machining process takes place. The final cross section of the substrate is obtained through several focused ion beam milling iterations referred to as loops. The ion doses required to attain the shape targeted after the completion of the initial loop are calculated pixel by pixel. The selection of an appropriate beam diameter is very important because of the beam overlap in the adjacent pixel. When the beam diameter is large as compared to the pixel size then the incident beam not only affects the pixel on which it is incident but also affects the surrounding adjacent pixels leading to undesirable features than required on the substrate. In order to account for this, the appropriate beam size is selected and it is then used as an input to calculate the ion dose required at each pixel. It was observed by Vasile et al. that the angle of incidence of the ion beam also plays an important role in the calculating the sputter yield. The angle of incidence changes from pixel
to pixel while machining curved features; hence, the material removal rate also changes. Vasile et al. used the Yamamura formulation to analyze the angular dependence of yield with the result he had obtained. The Yamamura formulation was dependent on the Sigmund formulation. According to Vasile et al. for milling each point, the required sputter yield which is a function of ion beam incident angle and dwell time is computed separately in a mathematical model derived by Yamamura et al. (Fu & Bryan, 2004; Langford et al., 2007). However Vasile's results showed that maximum yield is obtained at an angle of approximately 80°. The yield decreases as we increase the angle further. A crucial difference between the two formulations was that, at a high angle of incidence the Sigmund formulation gives a yield which is close to zero which does not go along with the observations of Vasile et al.. Hence, Vasile used the Yamamura formulation for his experiments (Adams and Vasile, 2006). The sputter yield varies from conducting to non-conducting materials for the same ion dose and pixel dwell time (Mulders et al., 2007). In the case of non-conducting materials, the ion dose accumulates while milling, and this causes the ion beam to deflect. This can be avoided by using layer of conducting material over the surface of the non-conducting material being machined (Mulders et al., 2007).

Appropriate selection of pixel dwell time depends upon the number of times the ion beam is repeated/passed over the substrate. For small repeat numbers the dwell time is large. For large dwell times the repeat number is small. This gives us a range of suitable dwell times and helps us to understand the optimal process parameters (Adams & Vasile, 2006). Vasile et al. simplified the experiment in order to reduce the number of measurements to different values of sputter at different angles, and then they assigned a single value of sputter yield at a particular angle. Vasile et al. observed that for small repeat number for the ion
beam the dwell times are large and the bottoms are rarely milled flat as compared to the process using large repetitions of the ion beam. Vasile et al. also observed that a tilted facet leads to non-uniform material removal rate leading to asymmetric features on the substrate.

While choosing a large repeat number Vasile et al. had to consider two other factors. One was the unintended exposure of surrounding pixels to ion beam due to non rectilinear features such as circles, ellipse, and polygons. This unintended exposure leads to undesired features on the substrate. The other factor was the extraordinarily large repeat numbers leading to extraordinarily small dwell times at every point which then is difficult to control. In order to eliminate these drawbacks they selected an appropriate range of dwell time and carefully selected the repeat numbers for the ion beam. This problem was mitigated by choosing lower repeat numbers and restricting the ion dose to unwanted areas. In an experiment conducted by Yamaguchi and his co-workers they tried to mill a cavity in Si substrate using single pass and repetitive pass scheme. They found that in repetitive pass scheme the amount of sputtered material in each pass is very less and is also proportionally smaller as compared to single pass scheme (Tseng, 2004). The sputtered material in the previous pass of the beam is also removed equally in subsequent passes of the ion beam. It is because of these reasons that Yamaguchi et al. found that repetitive pass scheme of milling leads to a uniform milling of the profile (Yamaguchi et al., 1985). In order to machine a smooth profile on the specimen, the ion intensity rate or the ion flux should also be maintained constant with respect to the scanning direction (Tseng, 2004). In addition to this the pixel spacing should be small enough to allow proper overlap of the adjacent scanning lines. These problems faced by Vasile are inherent to modern day commercial focused ion beam systems.
Vasile et al. also tried to control the depth of milling for a 3D micro structure by using the address mode deflection beam writing. The procedure they followed to control the depth was similar to the process they followed in varying the pixel dwell time. The main idea of address mode deflection beam writing is to direct the ion beam onto the object which is being sputtered. This feature created by ion bombardment is then mapped into a digital image using information from the secondary electrons ejected. The dwell time technique used in this process uses a characteristic length called the repair length in the pixel address pattern. The repair length can be defined as a program for pixel dwell time increment or decrement according to the desired geometric feature (Vasile et al., 1997). Using the address mode deflection beam writing method Vasile et al. fabricated various shapes such as parabola, circles, sinusoidal geometries, and rectangles or squares. He used the ion beam deflection calculation software for calculating the depth at each of the pixels for the various geometries. The dwell time in the program for the ion beam deflection method was dependent on the relationship of the repair length (dictated by the geometry, the symmetry) (Vasile et al., 1997). The output from the experiment conducted using the deflection beam method showed that the ion beam control program provides a good first approximation. It also provides geometries with desired features and depth except, for geometries with steep cuts.

Other factors that can significantly affect the focused ion beam milling process are: (1) the relationship between the sputter yield and the incident ion beam angle, (2) the effect of step change in the dwell time due to change in the dimensions of the pixels. It means that for example; for milling a parabolic curvature, a smaller step size would give a better surface profile than a larger step size (Vasile et al., 1997). According to Vasile the sputter
yield is a material property. The sputter yield can be defined as the volume of material removed (μm$^3$) from the object being machined from a unit dose of ions (nC). The sputter yield represents the efficiency of the material removal process (Tseng, 2004; Tseng, 2005). It is also referred to as the milling yield (Mulders et al., 2007). Hence, a definite relationship between sputter yield and the incident ion beam angle cannot be determined. The higher the amount of the sputter yield and angle of incidence, the more is the proportion of corrections required to achieve the required geometry (Vasile et al., 1999; Reyntjens & Pueurs, 2001).

The sputter yield maintained a direct relationship with the ion energy. In the first part of the curve plotted with the help of TRIM (Transport of ions matter- it is a software package based on Monte Carlo program (Tseng, 2005) to determine sputter yield for different ion energy and mass) the yield increases exponentially with an increase in ion energy. And then, at the end part of the curve, as the energy increased the sputter yield does not increase in the same exponential manner as before, due to increase in depth (Tseng, 2004). In a research conducted by Mulders et al.; they observed that the sputter yield values predicted through experimentation on various materials such as aluminum, brass, titanium, and phosphor bronze are higher than the measured values (Mulders et al., 2007). The other main factors which determine the sputter yield are the masses of the ions and substrate atoms, ion energy, target temperature, and ion flux (Tseng, 2004).

As mentioned earlier the focused ion beam systems are an efficient and precise way for manufacturing high precision tools used for micro or nanosize fabrication. These tools are very small and delicate and fabricating them by employing normal fabrication methods would render the tools useless. The modern machines which have the spindle rotating on high precision air bearings, equipped with high precision work tables are able to machine
tools to micron precision, by the conventional material removal process (Vasile et al., 1999). The micro sized features produced by this conventional process of machining depend upon two factors. The first is the diameter of the rotating tool. The second factor being the relationship between the forces generated by this rotating tool and the strength of the material that is being machined (Vasile et al., 1999). The feed rate and the corresponding material removal rate depends upon all of these parameters. A slight variation in the material properties with the correct feed rate also causes the tool to break and may lead to wastage of high cost material being machined. Such drawbacks are not faced with the focused ion beam machining process since it uses a beam of Ga or He ions which have very little effect due to change in the material characteristics.

According to the Yamamura formulation, the sputter yield for Si subjected to a 20 keV Ga\(^+\) ion beam, the peak sputter yield is reached at an angle ranging from 70\(^0\)- 80\(^0\). The sputter yield observed in this region is approximately three times as much as that observed in the range of 0\(^0\) – 45\(^0\) (Vasile et al., 1997; Yamamura et al., 1983; Mulders et al., 2007). The surface binding energy which keeps the atoms in the substance bound together is a property of the material melting temperature. When this binding energy is overcome the atoms are sputtered away. For a material with low melting point, the sputter yield is high. Conversely for a material with a high melting point the sputter yield is low (Mulders et al., 2007). The pixel size and the ion beam diameter considered is an integer; hence, the depth calculated by the formula also gives an integer. However, for profiles with curvature, the depth may not be an integer value; hence, the problem of depths at the bottom of the profile arises. A larger pixel size gives a coarse resolution for the profile while a smaller size gives a more fine profile (Vasile et al., 1997).
The microscopic surgical tools and manipulators used to measure the pressure of the arterioles and venules of small animals (mice and rats) are produced with the help of a focused ion beam machine. These micro surgical manipulators produced are capillaries of uniform thickness with the ends lacking a specialized geometry. They are very fragile. A program was initiated in the Louisianan State Medical College to ion mill these micro manipulators in stainless steel so that they could stabilize the tissue surrounding the test vessel and for occlusion of the vessels (Vasile et al., 1999). The fabrication of the micro manipulators is a two part process. In the first part of the process, an anodic tapering of a commercially available stainless steel needle is done. This is carried out to reduce the amount of ion milling required to obtain the specific geometry of the manipulator. In the second stage, the anodized stainless steel object is ion milled, with a deflection program to obtain the final product (Vasile et al., 1999). A high current ion source is used to manufacture these micro surgical tools and manipulators efficiently and economically. The main advantage of fabricating tools for different applications by using focused ion beam is that, almost any conceivable geometry of the tool can be obtained on a scale where the normal tool grinding method cannot be used (Adams et al., 2000).
2.2.2. Slice By Slice Cut Approach. Fu and Bryan made similar attempts at milling micro structures by using constant sputter yield and pixel dwell time. They tried to eliminate the drawbacks from the Vasile’s method by keeping the dwell time and sputter yield constant. Fu’s method was based on the theory of converting a 3D structure into a 2D structure by cutting it into thin slices of equal thickness. This was the main difference between the methods reported by Vasile and Fu. Vasile varied the pixel dwell time and ion dose to achieve the structure for 3D cavities. Fu achieved the same 3D cavities by dividing the structure into thin slices and then machining each slice at one time. When these milled slices were put together they formed the required 3D cavity. If the 3D structure is divided into ‘S’ number of slices to form the required cavity, then the entire cavity is formed after ‘S’ number of milling steps.

The profile of the cavity to be machined, determines the quantity of the slices that the substrate needs to be cut in. The steeper the profile of the cavity the more would be the number of slices. In practice, beam overlap is necessary for a focused ion beam system. Negative overlap means there is a space between adjacent pixels being scanned by the beam. Positive overlap means that the ion beam removes material from adjacent pixels also (Fu et al., 2000). Fu used an MDDL program to input the required parameters into a computer, which then passed the directives to a focused ion beam milling machine to process the 3D cavity. For simplicity Fu et al. milled a spherical cavity. They showed that the surface roughness of the spherical cavity decreases exponentially with an increase in the number of slices. However, the milling time increases non-linearly with the increase in the number of slices. Conversely, the larger the slice thickness the worse would be the surface roughness and at the same time the milling time would be less. For a large slice number, the ion dose
required per pixel is less as compared to the ion dose required for a small number of slices. According to Fu et al., the milling time for slices with constant thickness depends upon the current beam with the ion dose remaining constant. It decreases exponentially with the increase in the beam current (Fu & Bryan, 2004). According to Fu et al., the material being milled also plays an important part in the surface roughness issues. The more the material is crystalline, the higher would be the surface roughness. Focused ion beam milling systems are more appropriate for non-metal materials (Fu & Bryan, 2004).

2.3. CHALLENGES IN FOCUSED ION BEAM MACHINING

In order to find out the appropriate range of dwell times for sculpting Vasile et al. performed a certain experiment on sculpting silicon into various shapes. Shapes such as hemisphere, parabola, and sinusoidal wave form were sculpted in the silicon substrate. The first observation that he made was that even though the targeted geometries were reached there was slight roughness and rounding at the edges of the features produced. This roughness was due to the effect of the incident ions on adjacent pixel which produced machining effects on them. The other observation that was made was that the features sculpted had a flat bottom. The depth of the feature sculpted was relatively less than the intended depth of the feature. The depths were less in the deepest regions of the feature while the depths adjacent to the steep faces were approximately the same as the required depth. This problem of shallow depths that occurred was due to the effect of ejecta deposition. Ejecta deposition is caused due to milling of pixels adjacent to the required pixel which gets deposited on the area which has already been milled. The effect of ejecta deposition is observed less at $0^\circ$ angle of incidence, and the effect goes on increasing as the angle of incidence increases. Such shallow features were observed by Vasile regardless of
the range of dwell times used. The re-deposited ions on the nearby surface created round edges and arbitrary shaped features which are not intended in the final geometry of the required specimen (Mulders et al., 2007). Very little is known about how to eliminate these effects of re-deposition. For structures that have high aspect ratio, re-deposition will fill up the side walls, and prevent the formation of a clear structure.

In order to overcome the effects of ejecta deposition Vasile provided additional ion dose at the areas which were away from their required depths. This led to near required depths for the feature milled. It is necessary to know the characteristics of the shape formed and the properties of ejecta deposition to recalculate the new amount of ion dose required at the respective point. Despite the consistent errors introduced by ejecta deposition Vasile considered this to be reasonable and attempted to eliminate these errors on learning more about the spatial distribution of ejected atoms and its dependency on the angle of incidence. Another idea proposed by Mulders et al., to counter the effects of re-deposition, is to have an extensive study of the chemistry of the materials. This included applying an extra layer of suitable material over the material being machined to create a volatile compound that would eliminate and reduce the effects of re-deposition by a large extent (Mulders et al., 2007). According to Mulder et al. a lower beam current and faster dwell times could also eliminate the adverse effects of re-deposition. However, this would make the process time consuming since the rate of machining would be low with small beam current. The other problem faced by Vasile’s method was that, since the ion dose was needed to be calculated for each point to obtain the required milling depth, the program became too long. It also occupied a lot of computer memory and required special computers to process the task; for example milling an area of (15 x 15) µm² the memory required was approximately 50 megabytes. It also
required a longer time to complete the task (Reyntjens & Puers, 2001). It took approximately four hours for finishing the milling of the respective area. Calculating the dwell time and the amount of ion dose every time for each pixel is tedious and time consuming. Because of these drawbacks it is used for small scale production, post processing, and prototype manufacturing (Reyntjens & Puers, 2001).

The drawbacks from the variable dwell time approach such as insufficient computer memory and longer processing time were eliminated by the method proposed by Fu and Bryan. They proposed a dwell time and sputter yield milling process. They transferred a 3D microstructure into a 2D micro structure by dividing the 3D structure into thin layers. The thin layers were cut in such a manner that their thickness was kept constant. The milling depth for each slice depends on the slice thickness (Fu et al., 2000). Also, the problem of depths for the milled areas is eliminated by using Fu’s method. This is because, as the object is divided into thin slices, the effect of the ion beam on adjacent pixels is less. Hence, when we add up all the slices together, the total milling depth is almost the same as the required depth. The effects of ejecta deposition are negligible in this case. For beams having low or high currents (200pA - 1000pA) the surface roughness was a major concern. For low beam current surface issues such as circular marks are retained on the boundary of each slice. For high beam currents features such as scattered ripples of the sputtered material were observed. Both these unwanted features lead to surface roughness issues with the constant dwell time method. A moderate range of beam current yields better results with respect to surface roughness. The surface roughness values strongly depend upon the curvature of the profile. The surface roughness and the nature of the profile have a direct relation between them. The surface roughness is high for slices which have a high profile and curvature and
vice versa. The 2D slice by slice cut approach has the following advantages over the other methods reported till date. The grain structure of polycrystalline materials is known to limit the surface finish (Vasile et al., 1999). It also leads to an increased value of the dimensional tolerances for the object being machined (Vasile et al., 1999). Advantages such as a simple mathematical model, less memory usage, and faster fabrication speed were displayed by the slice by slice cut approach. The 2D slice by slice cut approach can be used for fabricating symmetric as well as asymmetric features.

The deflection beam writing method developed by Vasile et al. had more complications since the method was developed even before they had proposed the variable dwell time approach. As mentioned earlier the effect of re-deposition during ion milling various geometries cannot be neglected. Effects of re-deposition can be reduced to a very low level; however, the adverse effects produced due to it cannot be completely eliminated. However, the pixel resolution and the angle of incidence can be corrected (Vasile et al., 1997). For the deflection ion beam writing method, the size of the pixel is large as compared to the smallest diameter of the beam that can be used for milling using a focused ion beam machine. This leads to the effect of ‘overlap’. This exaggerates the ion dose received at the respective pixels. However, this problem was eliminated in a later study by Vasile. The method developed in this research, also eliminates the problem of beam overlap which might produce unwanted effects on the feature being milled on the substrate.

In a research conducted by Reyntjens and Peurs (2001), they found that focused ion beam process induces small amounts of damage in the samples under consideration. This damage includes implantation of high energy ions, amorphization (swelling) (Tseng, 2005) of crystalline structures, mixing of components, and loss of fine structural detail. In order to
prevent this, they suggested the application of a layer of other metal such as platinum prior to use by a focused ion beam system for top surface damage (Reyntjens & Puers, 2001).
3. THE MODEL

3.1. SYSTEM SETTING

In general, consider a rectangular parallelepiped of dimensions ‘x’, ‘y’ and ‘z’ units along the X, Y and Z direction. It is divided into a grid of pixels for ease of machining. The parallelepiped used for the modeling purpose is represented in Figure 3.1. The feature is fabricated into the rectangular parallelepiped with the help of a raster scanning method. In the raster scan process, on completion of the scanning of a grid of pixels on the same axis, the scanning process starts from the adjacent pixel below the original starting point. For example, features or cavities such as a spherical lens, a parabolic trough, and many other features can be fabricated into the rectangular parallelepiped. The maximum dimension of the feature that is to be milled is generally kept equal to the maximum dimension of the rectangular parallelepiped into which the feature is to be fabricated. The dimension of the feature can also be slightly less than the maximum dimension of the rectangular parallelepiped. Consider that the rectangular parallelepiped is divided into a grid of pixels along the ‘X’ and ‘Y’ direction. The number of pixels into which the rectangular parallelepiped is divided depends upon the external dimensions of the rectangular parallelepiped and the respective size of each pixel on that the rectangular parallelepiped.

For example, let us assume that the rectangular parallelepiped is divided into ‘m’ rows and ‘n’ columns with each pixel size of Δx length and Δy breadth, such that Δx= Δy units. Hence, the number of rows actually present on the substrate can be represented by the formula, \( m = \frac{X}{\Delta x} \); whereas the actual number of columns can be represented by the formula \( n = \frac{X}{\Delta y} \). Considering the setting parameters, the number of rows (n) would be equal to or not equal to the number of columns (m). Hence, the total number of pixels on the
cube would be a large number \( N = m \times n \) pixels. It can be assumed that the product of number of rows and number of columns represented as ‘N’, represents the actual total number of pixels that are physically present on the object, whereas the total number of pixels from the columns \( M \) \( (M \leq m) \) represents the pixels that are going to be machined. This phenomenon of dissimilar number of rows and columns can be explained by considering the step size. Step size provides us the flexibility to machine every pixel or every alternate pixel and so on. This radically reduces the machining time, which is one of the objectives of the research.

![Figure 3.1 Parallelopiped Used For Experimentation](image)

The very high number of small sized pixels would help us in maintaining a high quality of the milled surface irrespective of the beam used. This fact depends upon the beam
diameter being employed and the corresponding pixel size employed for machining. Naturally a larger beam would lead to faster machining but to a lower quality as compared to the smaller beam. The smaller beam would take a longer time to process the machining, but would lead to production of a superior surface finish and closer tolerances. This can be explained as; the use of larger beam would mill larger surface area, but when milling features that require characteristics that are smaller than the beam diameter the larger sized beam fails. This is because the larger size beam overlaps the adjacent pixels resulting is lesser accuracy for the feature to be milled. While the smaller beam, on the other hand, covers a much smaller pixel area and the smallest diameter beam can be successfully used to mill features which are in micro/nano scale. The pixel dimensions that are set in the experiment are slightly smaller than the smallest beam diameter which helps in machining the micro/nano features more accurately. The reason for deciding such a small size is explained later in the results section.

A raster scanning method is used to produce the respective depths at each pixel. In raster scanning, each pixel is scanned from left to right until all the pixels are covered by the machining process. In raster scanning, the scanning proceeds only in one direction throughout the entire process as shown in Figure 3.2(a). The other type of scanning method is the serpentine scan. In this, the direction of the scan reverses after every pass for the entire process (Tseng, 2004). The serpentine scanning process is represented by Figure 3.2(b). The serpentine type of scan also reduces the re-deposition effects, since the direction is reversed after every pass, leading to a smooth and uniform milled surface (Tseng, 2004). For research purposes, raster scan is employed since it has better beam control. However, it lowers the processing speed of the entire system. The scanning sequence should initiate with the pixels
where the least depth is required and end with the pixels where highest depth is required. This is done to avoid re-deposition effects (Tseng, 2004).

The depths are milled on the rectangular parallelepiped by employing the code, created in MATLAB using quadratic programming. The MATLAB code created is transformed into mechanical movements through a computer connected to the focused ion beam machine. The depths which are then milled by the focused ion beam machine are then compared with the objective function $Z_i^0$. The thesis further discusses the two examples that are used to demonstrate experimental analysis. One being the spherical lens, whose objective function is, $Z_i^0 = \sqrt{R^2 - x^2 - y^2}$. The other example considered is a cavity of uniform depth.

Where 'R' represents the dimensions of the feature to be milled on the parallelepiped and ‘x’ and ‘y’ represent the distance between the reference pixel and the actual pixel being machined along the X and Y axes. This is done to check whether the quality produced by the focused ion beam machine is within the tolerable ranges. In order to find whether the quality of the fabricated feature is within tolerable range, an iterative process is used. The iterative process is set up to reduce the machining time according to the quality specified. The tolerance range is set within the MATLAB code that is used for machining purposes. If the time produced in the first iteration is not up to the level that is expected, then the iterative process is continues till the set tolerance is achieved. In the iterative process, the solution obtained in the first step is used as the input for the second approximation, which is then compared with the tolerance set (for checking the time). If the obtained value is less than the specified tolerance value then, the solution is accepted; if not the process repeats, till acceptable solution is reached.
Figure 3.2 Scanning Methods

(a) Raster Scan; (b) Serpentine Scan;
(1) Beam Diameter; (2) Scanning Path; (3) Grid Of Pixels

The function used to obtain the required depths on the rectangular parallelepiped to produce a spherical lens (example 1) can be obtained by using one of the constraints of the quadratic program. This function considers the Gaussian distribution effect while calculating the depths at each pixel. The Gaussian distribution effect considers the effect produced around the adjacent pixels also, to give a total effect produced by the ion beam incident at a certain pixel. The constraint used for the depth calculation can be divided into two groups for ease of calculation. One group is the constant terms and the input parameters and the second group is the decision variable which needs to be determined. Once the depths are obtained, the decision variable, which is time in this case is determined and then the linear
equation is compared with the objective function to ensure that the error is kept to a minimum low ($\varepsilon$) (value in nano meter). The low error between the two models ensures that the quality of the product produced is in the acceptable region of tolerance. Even though, the iterative process is used, there is no significant increase in processing time and the process is still quicker than other methods that are currently being employed in the market. This provides an advantage to the model that we propose over the other models being currently employed.

3.1.1. The Decision Variable. Since the main aim of the research is to optimize the process planning for fabricating 3D nano or micro objects, the decision of the entire process depends upon how quick the process can be completed, for the given parameters and constraints. Since the efficiency of the entire system directly depends upon the processing time required to obtain the required feature on the substrate, the time required for machining is the decision variable. It is expressed as $t_j^s$.

Where, $s = \text{a beam of different sizes where } (s = 1, 2, \ldots, T)$, and

(j) = the pixel where machining is being performed ($j = 1, 2, 3, \ldots, m$).

(i) = the pixel where machining effect is observed. ($i = 1, 2, 3, \ldots, n$)

The object to be fabricated is divided into a number of pixels, consisting of rows (n) and columns (m). The decision variables are represented by a column matrix consisting of ‘n’ rows and one column. The experiment being performed determines the number of columns of the object being machined depending upon the input parameters. The input parameters which are considered for determining the number of columns are the dimension of the cube along the Y-direction, the corresponding pixel size and the step size used. Both the dimensions are in nano meters and the step size is just a number.
3.1.2. The Constraints. The instrument used for machining nanosized features on the substrate is a focused ion beam milling machine. In this machine, a charged beam of ions or electrons is directed with the help of a mechanism towards the substrate. The substrate is divided into a grid of pixels for ease of machining and also for accurate machining.

The user can select a beam from a wide range of beam widths, according to the required feature on the substrate. The beam size also depends upon the surface finish and tolerance required on the substrate feature.

If the charged ion beam is applied say at a certain pixel \((x_j, y_j)\) to produce the required feature then the pixels which are in the immediate vicinity of the pixel which is being machined, (in this case \((x_i, y_i)\)), also experience the effect of machining due to machining on pixel \((x_j, y_j)\), but to a lower extent. This is represented by the side walls of the bell curve shown in Figure 3.3. The machining effect produced at the point of application of the beam at pixels \((x_j, y_j)\), is represented by the peak in the Gaussian distribution curve shown in Figure 3.3. Let us call these pixels which are in the vicinity of the effect of the machining process being done at pixel \((x_j, y_j)\) as \((x_i, y_i)\). This phenomenon can be compared with the Gaussian model (Tseng, 2005) or normal distribution.

Gaussian distribution model is a continuous probability distribution that is often used as a first approximation to describe real-valued random variables that tend to cluster around a single mean value. The graph of the associated probability density function is ‘bell’ shaped, and is known as the Gaussian function or ‘bell curve’. It is the most widely used probability distribution in statistics since it is easy to use and can be modeled for a variety of random variables.
The standard normal distribution is given by,

\[ F(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \] Equation 3.1

Figure 3.3 The Gaussian Distribution

In this case, the operation at \((x_j, y_j)\) affects the neighboring pixels and vice versa. Hence, the ultimate depth \(Z_i\) can be shown as the aggregate result from all of the operation on the grid pixels. The equation can be shown as follows,

\[ Z_i = \sum_{j=1}^{M} Y_j t_j^i \left( e^{-\frac{[(x_j-x_i)^2+(y_j-y_i)^2]}{2\sigma^2}} \right) \] Equation 3.2

Where \(Z_i\) = is the depth being machined.

\((x_j, y_j)\) = the pixel where the actual machining is carried on.
\((x_i, y_i)\) = the pixel where the machining effects are observed due to actual machining carried on pixels \((x_j, y_j)\).

\(Y_s\) = the erosion rate in µm/s. It varies for different diameters of the beam.

The different diameter of the beams is represented by ‘s’.

\(\sigma\) = the standard deviation for the beam’s.

The constraint for quality can be written as,

\[
\|Z - Z^0\|_2^2 \leq \varepsilon \quad \text{.........................................................Equation 3.3}
\]

Where, \(\varepsilon\) is a very small arbitrary value which denotes that the machining objective achieved is within the allowable range (tolerance limits).

The number of rows in the coefficient matrix represents the total number of constraints. The object to be machined is divided into array or rows \((n)\) and columns \((m)\) to form a grid of pixels for ease of manufacturing. The grid size is kept independent of the ion beam under use so that the quality of the milled feature is not compromised. The number of rows in which the object needs to be divided is determined by the dimensions of the object and the corresponding pixel size. The rows are represented by ‘n’. The formula stated in Equation 3.2 is simplified for the purpose of MATLAB coding. The formula in Equation 3.2 contains constant terms and a decision variable. After modifying the formula for Gaussian distribution it can be grouped into two terms, one containing the constant terms and the other part containing the decision variable. The grouping of terms also helps us to convert a non-linear appearing type of equation into a linear type of equation. These constraints are represented by the number of rows in which the object is divided into; to form a grid of
pixels. These are known as the main constraints. The other constraints are the non-negativity constraints. The non-negativity constraints imply that the decision variable value cannot be negative. It is so, because the decision variable in our case happens to be machining time.

The transformed equation then can be represented as,

\[ a_{ij} = Y_s \left( e^{-\frac{[(x_i-x_j)^2 + (y_i-y_j)^2]}{2\sigma^2}} \right) \] …………………………………………Equation 3.4

This transforms the previously looking non-linear equation into a linear format. The linear format can be represented as into

\[ \sum_{i=1}^{N} \left( \sum_{j=1}^{M} \left| (a_{ij} * t_j) - Z_{ij}^0 \right| \right) \leq \varepsilon \]

Where,

- \( Z_{ij}^0 = \) the objective function value which is practically not possible to be obtained due to machining errors, human errors, coding errors, and other loses.
- \( A_{ij} = \) the coefficient matrix containing the constant terms
- \( \varepsilon = \) very small arbitrary value which denotes that the machining objective achieved is within the allowable range (tolerance limits).

The terms that are grouped into one category for ease of coding are the erosion rate \( (Y_s) \), the coordinates of the point being machined \( (x_j, y_j) \) and the coordinates of the pixels \( (x_i, y_i) \) where the machining effect is observed in the vicinity of the pixel being machined, the standard deviation and constant term \( \pi \). The standard deviation value remains constant for a specific setting.
For the model under consideration the processing efficiency is the main constraint. Processing efficiency can be defined as the time taken by the focused ion beam machine to mill the required feature/cavity on the substrate. The constraint for quality is taken into consideration by designing the MATLAB code in a different way than the regular way by incorporating the boundary conditions and thorough the iterative process.

3.1.3. The Objective Function. The objective of the quadratic optimization, setup for the fabrication of nano scaled products considers not only the processing time but also the quality of the product fabricated. Normally, with reduction in the time required for fabricating (producing) a product, it leads to a decrease in the quality characteristics of the concerned product. Quality traits such as surface finish, dimensions of the product and tolerances and its interior structure characteristics are also affected.

The objective of the quadratic optimization, setup for the fabrication of nano scaled products considers not only the processing time but also the quality of the product fabricated. Normally, with reduction in the time required for fabricating (producing) a product, it leads to a decrease in the quality characteristics of the concerned product. Quality traits such as surface finish, dimensions of the product and tolerances and its interior structure characteristics are also affected. A larger beam size leads to higher rate of material removal but leads to a lower quality of the finished surface. On the other hand, a smaller sized beam leads to lesser material removal and higher machining time but a much finer surface finish. Therefore, the objective for the optimization of processing plan is to minimize the total processing time beyond satisfied surface resolution.

Since the objective is to increase the overall process efficiency of the manufacturing process without compromising on the surface finish and at the same time reducing the
processing time required for fabricating the object, within the tolerance limits, the objective function can be stated as,

Minimize cost function,

$$ f(t) = \sum_{i=1}^{N} \left( \sum_{j=1}^{M} a_{ij} t_j^s - Z^0 \right)^2 + \lambda \sum_{j=1}^{M} t_j^s \quad \text{Equation 3.5} $$

Where,

$$ t_j^s = \text{the dwell time for the beam’s at pixel which is being machined at} $$

$$ (x_j, y_j) \text{ and } j = 1, 2, 3, \ldots, m. $$

$$ (x_i, y_i) = \text{the co-ordinates for the pixel adjacent to the pixel where actual machining is being carried on where } i = 1, 2, 3, \ldots, n. $$

$$ s = \text{different beam sizes from } s = 1, 2, 3, \ldots, T. $$

$$ M = \text{total number of pixels on the object actually.} $$

$$ N = \text{total number of pixels actually being machined.} $$

$$ \lambda = \text{the weight put on the milling cost, where } \lambda \geq 0 $$

3.1.4. The Mathematical Model. To sum up all the description about the system setting, the decision variable, the constraints and the objective function the mathematical model for the entire system can be represented as,

$$ a_{ij} = \text{the individual coefficient matrix values in the coefficient matrix containing the constant terms as discussed above.} $$

$$ t_j^s = \text{the decision variable} $$
\( Z_i^0 \) = the objective function which provides the exact dimensions of the feature that is being milled with the help of the focused ion beam.

\( \lambda \) = the weight put on the milling cost, where \( \lambda \geq 0 \) and for ease of calculation we assume it to be equal to zero.

\( \sigma_s \) = the standard deviation of the beam of a specific diameter and is also a constant number (input).

\( (x_j, y_j) \) = the pixels where actual machining is being carried on

\( (x_i, y_i) \) = the adjacent pixels in the vicinity of \( (x_j, y_j) \), where the machining effects due to Gaussian distribution are observed.

\( s \) = the different diameter beam sizes, \( s = 1, 2, 3, \ldots T \).

Minimize,

\[
f(t) = \sum_{i=1}^{N} \left( \sum_{j=1}^{M} a_{ij} t_j^s - Z_i \right)^2 + \lambda \sum_{j=1}^{M} t_j
\]

Subjected to the following constraints,

\[ t'_j \geq 0; \forall j \]

3.2. OPTIMIZATION ALGORITHM

The method used for optimizing the quadratic program is different from the normal linear programming optimization. A MATLAB code is setup to achieve the optimization. As seen from the above mathematical model the optimization program is subjected to non-
negative constraints ($t_j^i \geq 0; \forall j$). In such cases, an optimization code developed by Sha et al. is used which provides multiplicative updates to converge to the global minimum. The multiplicative updates improve the value of the objective function at every iteration which ultimately converges monotonically to the global minima (Sha et al., 2007). The updates provided by this process are simple and closed form and do not involve any heuristics or free parameters that would require some tuning to converge globally (Sha et al., 2007). The reason for the use of the iterative process arises because of the significant rounding errors introduced during calculation. The iterative process refines these solutions reducing the effect of rounding off errors (Gould et al., 2001).

The various iterative methods that are used to converge to actual solutions are the gradient descent, where the objective is obtained by additive updates. It is not particularly suited to constrained optimization as it can lead to violation of the constraints in some cases. The other simple and more appropriate method called the Exponential Gradient, it is a multiplicative update. Multiplicative updates such as the Exponential Gradient converge at a faster rate to the solution as compared to the additive updates (Sha et al., 2007). This is more true if the optimization problem is sparse, containing a large number of zero elements. Also, sparse solutions are likely to arise in problems with non-negativity constraints (Sha et al., 2007). The paper presented by Sha et al., provides us with a solution approach to a special case when the optimization is confined to an axis-aligned in the non-negative orthant. The paper presents multiplicative updates for convex problems in quadratic programming (Sha et al., 2007). The updates provided by the algorithm converge globally by exploiting the particular structure of the fixed points as well as the convexity of the objective function.
In the research, the MATLAB code developed basically consists of four parts- the row index, the column index, the objective function, the ideal objective function and the iterative process which uses the quadratic programming optimization method proposed by Sha et al., in their paper "Multiplicative updates for non-negative quadratic programming". The original objective function for example 1 is represented by equation, 

\[ Z_i^0 = \sqrt{R^2 - x^2 - y^2} \]. The most common form for representation of a quadratic program is,

\[ F(t) = t^T Qt + 2P^T t + \gamma \] .................................Equation 3.6

Subjected to,

\[ t \geq 0 \]

Where,

\[ Q = A^T A \]
\[ P = -A^T Z^0 + 0.5\lambda \times 1 \]
\[ \gamma = (Z^0)^T Z^0 \]

It is assumed that the matrix A is symmetric and is strictly positive definite, so that the objective function F(t) in Equation 3.6 is bounded below and its optimization is convex. A, e x f matrix is considered to be positive definite, when \( t^T \times A \times t \geq 0 \) for all nonzero vectors of ‘t’ (decision variable) (where e and f represent the dimensions of a given matrix) . The vector elements of P from Equation 3.6 might be negative or positive. The updates for a
special case like this in non-negative matrix factorization (NMF) are derived from an auxiliary function similar to the ones used in Expectation maximization algorithm (Sha et al., 2007). Their simple element-wise form can be shown as,

$$ t_{k+1} \leftarrow \left[ \frac{|P_t|}{Q_t} \right] t_k $$

Equation 3.7

Non negative factorization is a group of algorithms in multivariate analysis and linear algebra where a matrix $X$ is (usually) factorized into two other matrices, say $V$ and $W$. The validity for the updates provided by this algorithm for the non-negative matrix factorization depends upon the assumption that the matrix $A$ is non-negative; otherwise the denominator in Equation 3.7 would become negative leading to violations of the non-negativity constraints. This algorithm also holds true when the decision variable has an upper bound. In such case the decision variable is restricted to an axis aligned box in non-negative orthant.

The ‘$\lambda$’ in Equation 3.5 is the weight (importance) that is put on the milling cost. In our case the Missouri University of Science and Technology owns a Helios 600 FIB/SEM instrument of its own. As a result we can eliminate the importance attributed to the machining cost. Hence, $\lambda = 0$ in the research performed. However, different weights might be assigned to it depending on the type of machine being used. Missouri University of Science and Technology charges an amount of $406 per hour for the use of Helios 600
FIB/SEM for an external use. Considering this as the bench mark, appropriate weights can be assigned according to the type of machine and its usage.

3.3. SOLUTION

The algorithm used for the iterative process in Equation 3.7 can only be used when then numerator value for the algorithm (which is \( P = -A^T Z^0 + 0.5 \lambda \times 1 \)) is negative in value. When the value for the numerator increases with increase in the value of the weightage given to the milling cost the numerator becomes positive and the algorithm does not hold true, producing large amount of deviations and poor quality. Also the value of the decision variable goes on increasing with the increase in the value of the lambda (\( \lambda \)). Intuitively, this looks absurd as with increase in the cost for usage of a machine the machining time also has to increase. This is observed till the parameter ‘P’ is negative. But when the ‘P’ value increases beyond zero the decision variable value initially decreases but then starts increasing, which gives rise to the phenomenon of increasing machining time with an increase in the machining cost. Thus, the algorithm in Equation 3.7 becomes a special case for application, only when the numerator is negative or when it has a smaller value. In such case the updates provided by the algorithm do not converge to the global minimum. But in general applications the numerator would rarely be negative or a smaller value, because of the cost attributed to nano-manufacturing is important and then the value for ‘\( \lambda \)’ is always greater than unity. In order to eliminate this drawback, a new algorithm was devised on a similar ground which is applicable to any general case and not just one special case as with the previous algorithm.
The new code has the same constituent elements as the previous one (Equation 3.7), the only change that is visible is the change in the numerator function. The new algorithm is shown in Equation 3.8

\[
Q = A^T A \\
P = -A^T Z^0 + 0.5\lambda \times 1 \\
\gamma = (Z^0)^T Z^0
\]

\[
t_{k+1} \leftarrow \max[\frac{-P_i}{0}] \left\{ t_k \right\} \text{ Equation 3.8}
\]

Due to the use of the maximum function instead of the absolute function, as in the previous algorithm by Sha et al., the drawback created due to very large positive numerator is eliminated. Because, when the calculated value for \( P_i \) is negative or small, it becomes positive in the algorithm and the maximum of the two values \( P_i \) and zero is considered and similarly vice versa when the calculated value for \( P_i \) is positive. When the value for \( P_i \) is positive, which might happen due to very large value of lambda, then \( P_i \) gets converted into negative \( P_i \) and the maximum of \( P_i \) and zero is considered. When the numerator becomes zero the value of the decision variable also becomes zero, which indicates that there is no need to machine the concerned pixel. When large proportions of \( P_i \) become positive then more and more decision variables would become zero, which would indicate no need of machining. When the entire \( P_i \) vector becomes largely positive then all the decision variables would become zero, which would mean that there is no need to machine at all. Such a case would occur only for higher values of lambda. Thus the algorithm in Equation 3.8 also
supports the intuitive thinking that when the value of lambda is very high there is no need to machine.

Intuitively thinking, a larger value (infinity) of lambda (\(\lambda\)) tells us that it is not economically feasible to machine. The algorithm in Equation 3.8 takes into consideration this effect and correspondingly provides a solution to the decision variable. Thus, the algorithm formulated in Equation 3.8 can be used for any general application and not just for a special case. It is observed that the quality of the product produced remains same with increase in the value of the lambda. The time required for machining also remains the same with increase in the lambda value. The only effect due to the increased value of lambda is seen on the total machining cost, which is an important factor to be considered due to the high costs of processing and raw material.
4. RESULTS AND NUMERICAL ANALYSIS

4.1. THE INPUT PARAMETER TABLE

Table 4.1 displays the input parameters that are used for carrying out the experimentation.

Table 4.1 The Input Parameters For Helios 600 FIB/SEM

<table>
<thead>
<tr>
<th>Setting</th>
<th>Current (nA)</th>
<th>FWHM Beam Diameter (nm)</th>
<th>σ (nm)</th>
<th>Current Density (I) (nA/μm²)</th>
<th>Erosion rate Y_s (μm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.001</td>
<td>7</td>
<td>2.97</td>
<td>1.8043E+04</td>
<td>4.8716E+03</td>
</tr>
<tr>
<td>2</td>
<td>0.01</td>
<td>12</td>
<td>5.10</td>
<td>6.1190E+04</td>
<td>1.6521E+04</td>
</tr>
<tr>
<td>3</td>
<td>0.03</td>
<td>16</td>
<td>6.79</td>
<td>1.0356E+05</td>
<td>2.7962E+04</td>
</tr>
<tr>
<td>4</td>
<td>0.05</td>
<td>19</td>
<td>8.07</td>
<td>1.2219E+05</td>
<td>3.2992E+04</td>
</tr>
<tr>
<td>5</td>
<td>0.1</td>
<td>23</td>
<td>9.77</td>
<td>1.6674E+05</td>
<td>4.5019E+04</td>
</tr>
<tr>
<td>6</td>
<td>0.3</td>
<td>33</td>
<td>14.01</td>
<td>2.4326E+05</td>
<td>6.5679E+04</td>
</tr>
<tr>
<td>7</td>
<td>0.5</td>
<td>39</td>
<td>16.56</td>
<td>2.9018E+05</td>
<td>7.8349E+04</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>50</td>
<td>21.23</td>
<td>3.5312E+05</td>
<td>9.5342E+04</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>81</td>
<td>34.40</td>
<td>4.0348E+05</td>
<td>1.0894E+05</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>110</td>
<td>46.71</td>
<td>3.6473E+05</td>
<td>9.8477E+04</td>
</tr>
<tr>
<td>11</td>
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<td>140</td>
<td>59.45</td>
<td>3.1522E+05</td>
<td>8.5110E+04</td>
</tr>
<tr>
<td>12</td>
<td>20</td>
<td>427</td>
<td>181.33</td>
<td>9.6808E+04</td>
<td>2.6138E+04</td>
</tr>
</tbody>
</table>
The Table 4.1 represents the standard input parameters for the Helios 600 FIB/SEM instrument at the Missouri University of Science and Technology. The experimental analysis is carried out using the parameters, in Table 4.1. The current density (I) and the erosion rate (Ys) are dependent parameters, while the current (c) and standard distribution (σ) are the independent parameters. The values of ‘I’ and ‘Ys’ are dependent on the values of ‘c’ and ‘σ’ with others being constants. This can be illustrated by the following formulas,

\[
I = \frac{\text{current} \ nA}{2\pi\sigma^2} \quad \text{[Equation 4.1] (a)}
\]

\[
Y_s = I \times 0.27 \mu ms^{-1} \quad \text{[Equation 4.1] (b)}
\]

4.2. EXAMPLE 1

The MATLAB code produces a solution which converges to a global minimum. The quality constraint is not neglected and the best possible quality is obtained through the iterative process. It is observed that as the step size increases for a setting with a fixed beam size, the amount of time (processing time for producing the required feature on the substrate) required to produce the feature on the substrate goes on decreasing. It remains almost constant till it reaches the threshold step size, with slight reduction in value, and then goes on decreasing further with further increase in the step size. This is true because, when every pixel on the object is machined, the time is spent by the beam for machining every pixel. This total time is much higher than the total time spent in machining every second pixel. To explain this, assume an object to have 100 pixels. If we machine every pixel, that is all the 100 pixels, then the total machining time would be more than when we machine every
alternate pixel. When alternate pixels are machined, the number of pixels is 50. Also with an increase in the step size, the number of decision variables goes on decreasing, which in turn reduces the machining time since the number of pixels which require to be treated upon decrease. The time spent by the machine thus goes on decreasing linearly as the step size increases for a given setting.

The setting that is used to explain and interpret the result has the following parameters; current = 0.01 nA; sigma = 5.10; step-size = 2; delta X = delta Y = 6 nm; X = Y = 1200 nm; R = H = 3000 nm. The current and sigma values are standard parameters for a respective machine. The delta X (Δx) and delta Y (Δy) represent each pixel dimensions on the actual object, whereas X and Y represent the total dimensions of the substrate used for machining. The feature that is machined is a spherical lens with a radius equal to 3000 nm represented by ‘R’. The height of the substrate used for machining is represented by ‘H’. With a step-size of 2, the number of decision variables are reduced which helps in quicker and efficient machining. The number of decision variables when the step-size is 2, sigma = 2.97 and the dimensions of the substrate are as mentioned above, is found to be 10000 which is 75% less than the number of decision variables when the step size is 1. This largely improves the processing efficiency, considering the quality of the product.

The selection of the step size is an important criterion for different beam settings. The analysis of the factors for a suitable selection of the step size is discussed later in the section.

The figurative representation of the objective function is provided below in Figure 4.1. It is a column vector consisting of total number of pixels the object is physically divided into for the ease of machining. The plot is obtained for a spherical lens feature, where the
radius (R) and height (H) of the lens are provided as $H = R = 3000\text{nm}$, and $\Delta x \ & \Delta y$ are the pixel sizes in the ‘X’ and ‘Y’ directions, respectively. In general it is observed that highest depth values are obtained at the corner points of the substrate to be machined, as it should be. It is because the amount of depth produced at the point of application is highest and it decreases as we move away from the point of application.

![Figure 4.1 The Objective Function Plot](image)

Figure 4.1 The Objective Function Plot

$\text{current} = 0.01 \text{ nA}; \sigma_s = 5.10; \ R=H = 3000\text{nm}, \delta x = \delta y = 6\text{nm}$
The values obtained in the respective matrix confirm the explanation provided above. The phenomenon of c21 = c12 (that is c_{ij} = c_{ji}) is also observed here when we transform the column matrix into a square matrix.

The plot of coefficient matrix multiplied by the decision variable that is the time also leads to a similar plot as obtained in the Figure 4.1 for the objective function. This shows us that the MATLAB code produced, which considers minimizing the time and maintaining the quality of the product achieves the objective. In order to consider the quality, the iterative process is used, which improves the value of the decision variable at every iteration to achieve the objective of minimizing the machining time. The plot for the coefficient matrix multiplied by time is displayed below in Figure 4.2. It can be seen through the plot that the quality is not up to the expectation on the two sides of the substrate.

![Figure 4.2 Plot Obtained From Actual Machining](image)

step-size = 2; current = 0.01 nA; σs = 5.10; x=y = 1200nm, deltaX = deltaY = 6nm
This is because the substrate to be machined is divided into 40000 pixels, which is equivalent to 200 rows and 200 columns. The step size is fixed to 2 and the setting parameters are current = 0.01 nA, $\sigma_s = 5.10$; $x = y = 1200$nm; $\delta x = \delta y = 6$nm. Since the step size is fixed to 2, the last pixel (pixel number 200) on substrate cannot be machined for each row. Similarly, the last row on the substrate (row number 200) would not be machined due to the respective selection of step size. As a result the quality is compromised at the two sides of the substrate since there is no actual machining taking place on the last column of every row and the entire last row of the substrate. All the effect at these end pixels is produced due to the Gaussian effect which is described in the earlier sections. As a result these end pixels are left un-machined which produce errors in the feature when compared with the ideal objective function.

This drawback is eliminated by a simple modification in the MATLAB code, which necessarily now includes all the boundary pixels irrespective of the step size used. This modification reduces the error produced, shown in Figure 4.2, leading a more accurate feature being machined as compared to the ideal objective function. The Figure 4.3 graphically displays the change in quality as compared to Figure 4.2.
Figure 4.3 Corrected Machining  
step-size = 2; current = 0.01 nA; σs = 5.10; x=y = 1200nm, deltaX = deltaY = 6nm

Figure 4.4 displays the deviation of the machined feature from the ideal objective function. The large deviations at the end are attributed to the step size selection. Due to the selection of an even step size the last column of every row and the last row itself are not machined resulting in the errors as seen in Figure 4.2. The Figure 4.4 also displays some amount of error at the edges even when the last row and the last column are machined.
Figure 4.4 Deviation From The Ideal Objective Function (A*t-Z)
step-size = 2; current = 0.01 nA; σs = 5.10; x=y = 1200nm, deltaX = deltaY = 6nm

On completion of the iterative process, it is observed that the solution obtained for the decision variable is very close to the set tolerance from the first iterative solution. It is observed that when the solution for the iterative process is plotted against the number of iterations it follows an asymptotic graph as shown in the Figure 4.5. An asymptotic curve is one in which the distance between the curve and the axis reduces to zero as the curve tends to infinity.
It can be seen that for the specific setting the value decreases drastically for the first few iterations and then the change in values is very small. This is observed because of the rough approximation for the first few iterations. As the iterative process proceeds, the solutions obtained through the algorithm mentioned in Equation 3.8; approximates more refined solutions and terminates the process when finally the solution value as compared to the solution from the previous iteration is within the tolerance range set. The fall is very steep at the beginning and then the line runs almost parallel till to the X-axis till it reaches its termination point set by the tolerance level.

In order to present the visual presentation of the distribution of the error from the objective function, a histogram is plotted. In statistical analysis histogram provides an
estimate of the probability distribution of a continuous variable. The following Figure 4.6 would provide more details about the analysis for the standard error.

![Histogram](image)

**Figure 4.6 Histogram**

step-size = 2; current = 0.01 nA; $\sigma_s = 5.10$; $x=y = 1200$nm, $\delta x = \delta y = 6$nm

From the vector obtained, from the deviation of the ideal objective function, the observed value for standard deviation ($\sigma$) is 3.88441. The variance is observed to be 15.08865 and the mean for the sampling ($n$) is -0.26386. The standard error (S.E) for the sampling is given by Equation 4.2
\[ S.E = \frac{\sigma}{\sqrt{n}} \] .................................Equation 4.2

Where, \( \sigma \) = standard deviation

\( n \) = sampling (40,000 in the research performed)

The standard error is used, because it provides an estimate of the standard deviation computed for the entire sample population. Different samples drawn from the distribution would have different means. This would not provide us with a correct value of the error. Hence, standard error is used which provides the value of the error over all the possible samples of the population. The standard error for the specific setting is observed to be 0.0194220.

Confidence interval (CI) is a particular kind of interval estimate for a sampling used to indicate the accuracy or reliability of the estimate. The confidence intervals that are used for such analysis are 50%, 95% and 99%. Generally, 95% is the most widely used confidence interval. In statistical terms this can be explained as, a claim of 95% confidence, which simply means that the researcher has observed during the experiment or simulation something occurring, that happens only one time in 20 times or less. With decrease in the level of confidence the size of intervals also decreases.

\[ 95\% \ CI = \text{mean} \pm 1.96\times \text{SE} \] .................................Equation 4.3
According to Equation 4.3 the value of the 95% CI is observed to be (-0.2258, -0.3020). This shows us that error produced for the entire sampling is centered about zero. Such small value of error can be neglected and it can be concluded that the feature produced by the proposed machining process achieves the required quality set.

### 4.3. EXAMPLE 2

To test the reliability, accuracy and repeatability of the experiment, another example is considered. The feature being milled is a small cavity in a substrate of a large size, as compared to the dimensions of the cavity. This can be depicted as a small cavity of certain depth in a large size of a substrate of a few unit dimensions. The cavity milled is of uniform depth with straight edges. The same MATLAB code is used for achieving an optimized solution considering the quality of the product produced. The same constraints are applicable in machining this cavity also. The same setting is used as in the previous case where the current is 0.01 nA; $\sigma= 5.10$; delta X = delta Y = 6 nm, and the uniform depth of the cavity to be milled is selected to be 50 nm (Z direction). The dimension of the cavity in X and Y direction are 1200 nm respectively.

The ideal objective function representation in Figure 4.7(a) shows the depth of the cavity to be milled. It is a column vector consisting of total number of pixels the object is physically divided into for the ease of machining. The number of pixels on each side is same as in when the spherical lens example is used for experimentation. In general for the spherical lens, it is observed that highest depth values are obtained at the corner points of the substrate to be machined, as it should be. It is because the amount of depth produced at the point of application is highest and it decreases as we move away from the point of
application. But whereas in case of the cavity with uniform depth, the depth produced by application of the ion beam is uniform as seen from Figure 4.7(b)

Figure 4.7 Example 2
(a) Objective Function Plot; (b) A*; (c) Error Plot; (d) No. Of Iterations V/s Total Of Errors; (e) Histogram
current = 0.01 nA; σs = 5.10; depth = 50nm, deltaX = deltaY = 6nm; step-size=2
The plot of coefficient matrix multiplied by the decision variable, i.e. the time also leads to a similar plot (Figure 4.7(b)). When it is compared with the ideal objective function, the amount of error is displayed in the Figure 4.7(c). Thus, this proves that the MATLAB code produced, which considers minimizing the time and maintaining the quality of the product achieves the objective set. In order to consider the quality, the iterative process is used which improves the value of the decision variable in every iteration to achieve the objective set of minimizing the machining time. The plot for the coefficient matrix multiplied by time is displayed below in Figure 4.7(b). It can be seen through the plot that the quality is good because the error produced from the machined cavity of the ideal objective function is of the order of $5 \times 10^{-9}$ m. Such small errors are not visible to normal naked human eye, and can only be viewed under a powerful microscope. Since we intend on manufacturing structures of nano ($10^{-9}$m) scale, such small errors obtained after the set tolerance level, should be within the acceptable range.

As seen with the previous example, the initial solution value falls suddenly for the first few iterations, and then moves almost parallel to the X axis till the set tolerance value is achieved. The Figure 4.7(d) provides us with a more graphical representation of the same phenomena. From the histogram shown in Figure 4.7(e) the standard deviation, mean and the variance are observed to be 4.0037, -0.3226 and 16.0302. The standard error (S.E) obtained, given by the Equation 4.2, is 0.02001. This provides us with the value of the error over all the possible sample population. The Equation 4.3 provides us with the value of the 95% CI. It is observed to be (-0.2837, -0.3618). This shows us that error produced for the entire sampling is centered about zero. Such small value of error can be neglected and it can
be concluded that the feature produced by the proposed machining process achieves the required quality set.

4.4. SELECTION OF SUITABLE STEP SIZES FOR MACHINING AND DETERMINATION OF THE THRESHOLD STEP SIZE

Based on the results obtained in example 1, various numerical analyses are performed. The different numerical analyses performed on example 1 are the suitable beam overlap or selection of the best possible step size (threshold step size) for obtaining the best possible quality with minimum machining time. On observing the errors produced in the feature as compared to the ideal feature intended on the object for different step sizes it is seen that, there is a possibility of two or three possible solutions for step sizes. The graphical representation below in Figure 4.8 and Figure 4.9 illustrates the main analysis for the threshold step size.

The graphical representation below shows the deviations from the objective function. The settings imply to the input parameters selected for numerical analysis. Considering setting 3, it can be seen that, the error increases gradually at the start with the increase in the step size for machining. However beyond the step size 3 there is a sudden increase in the value of the error. Beyond this the error value increases steeply. So it can be determined based on this analysis that for setting 3, step sizes 1, 2 & 3 are suitable for machining. The selection of these step sizes can be done depending upon the time requirement and also the quality intended for the required feature.
The step size 3 is called the threshold step size as the deviation of the feature machined from the objective function increases rapidly beyond this step size. Use of the respective setting beyond the threshold step size would lead to improper machining of the substrate and a poor quality. This would not comply with the objective set for the research and hence use of step size beyond the threshold value is not recommended. The threshold step sizes are marked in the above graphical representation with filled circles. Similar observations can be made for the remaining settings namely Setting 5 and setting 7. Similar to setting 3, the threshold step size is indicated in the Figure 4.8, as solid circles.
For the setting 1 it is observed that the threshold step size is 1. The error increases exponentially beyond this step size as seen from the graphical representation in Figure 4.9. Another observation that is visible from the above two graphical representations is that, as the parameters for the respective setting increases the threshold step size for the setting also goes on increasing. For example, for setting 1 the threshold step size is observed to be 1, while for settings 3, 5 and 7 the threshold step sizes are 3, 4 and 5, respectively. This also explains that as the beam diameter increases, the step sizes over which it is efficiently operational also increases which can be used to remove larger material at the start of machining process. For smaller beam diameter the threshold step size is small and it produces bad quality of the substrate for larger values of the step size. Hence smaller step
sizes with smaller beam diameter can be used for machining high quality features with close tolerances.

4.5. SELECTION OF SUITABLE BEAM OVERLAP

Determination of suitable beam overlap is an important factor because this tells us more about the suitable step size selection range. As discussed in the previous analysis for the threshold step size, the amount of deviation for the machined part from the objective function increases beyond the threshold step size. This also indicates that the threshold step size is the minimum amount of beam overlap required for the specific setting to achieve the best possible feature machined on the substrate within the tolerances specified. Figure 4.10 explains the formula that can be used for determining the beam overlap is shown in the following equation.

\[ Beam\text{-}overlap = 1 - \frac{L}{d} \]

Equation 4.4

Where,  \( L \) = the distance between the centers of point of application

\( d \) = the diameter of the beam used for the specific setting
The Equation 4.4 can be explained as, when the distance between the centers is equal to the beam diameter being used for the specific setting then $L/d$ ratio becomes one and hence the beam overlap is equal to zero. Under this condition the two circles of influence just touch each other as a tangent. When the beam completely overlaps, that is when the point of application is the same; the value of $L$ is equal to zero. As a result the ratio $L/d$ becomes zero and the beam overlap is equal to 1. That is, it is a perfect overlap.

For the settings in example 1, that was tested for determining the threshold step size, the overlaps observed are 14.28% for setting 1, 25% for setting 3, 21.73% for setting 5, and 23.07% for setting 7. For example, the threshold step size for setting 1 is 1, hence the value of $L = 6$ nm and the beam diameter for setting 1 is 7 nm. According to the Equation 4.4, the beam overlap calculated comes out to be 0.1428. From this, it is observed that the appropriate range for beam overlap considering the different settings available lies within...
the range of 14% - 40%. Best possible quality for the feature can be achieved with the above beam overlap range specified for different settings and step sizes.

4.6. EXPERIMENTAL DESIGN DATA ANALYSIS

Table 4.2 and Table 4.3 provide more details about the error, the threshold step size and the total time required for machining for the respective beam setting for the corresponding step size.

Table 4.2 Experimental Results (Spherical Lens)

<table>
<thead>
<tr>
<th>Spherical lens example</th>
<th>Setting</th>
<th>Step size</th>
<th>Error (nm²)</th>
<th>Total machining time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>0.0076</td>
<td>209.66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1,027,230.79</td>
<td>117.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1,352,686.50</td>
<td>57.30</td>
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<td>3,249.99</td>
<td>7.41</td>
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<td></td>
<td>2</td>
<td>12,364.11</td>
<td>7.39</td>
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<td></td>
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<td>163,685.92</td>
<td>7.28</td>
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<td></td>
<td></td>
<td>4</td>
<td>533,399.74</td>
<td>6.40</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1</td>
<td>4,804.92</td>
<td>2.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>7,500.06</td>
<td>2.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>13,597.78</td>
<td>2.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>101,026.04</td>
<td>2.26</td>
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<tr>
<td></td>
<td></td>
<td>5</td>
<td>328,866.34</td>
<td>2.17</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1</td>
<td>7,254.47</td>
<td>0.478</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>7,733.42</td>
<td>0.477</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>11,009.26</td>
<td>0.476</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>15,625.13</td>
<td>0.474</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>19,248.89</td>
<td>0.474</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>41,120.54</td>
<td>0.474</td>
</tr>
</tbody>
</table>
The above Table 4.2 represents the total error seen in the manufacture of the feature when the final iteration is completed. It also represents the total machining time that would be required for a specific setting with respective step size. The red highlighted values represent the threshold step sizes and their corresponding errors and time. It is observed that the machining time decreases as the step size increases. This result can be proved intuitively, as when for a specific beam setting when the number of pixels that are being machined decreases the total time required to complete the feature would also decrease. This is because the total machining time for a feature is directly proportional to the number of pixels that are being machined and also the amount of material that is required to be removed. This fact can be explained visibly by considering the results obtained from the experimentation carried out on example 2 (cavity of uniform depth).

Another visible observation that can be made from the Table 4.2, is that the amount of error increases very gradually for a specific setting with the increase in the step size. However, beyond the threshold step size there is a sudden increase in the error. This can be explained by considering one of the settings illustrated in the Table 4.2. Considering setting 5, the error when the step size is 1, 2 or 3; is small because the dimensions for each pixel is 6nm and the beam diameter for setting 5 is 23 nm. So when the step size is 1, 2 or 3 the maximum distance between the point of application of two successive beam points (centers of the respective pixel) is 6, 12 or 18; which is less than the full width half maximum (FWHM) diameter of the beam for setting 5. As a result even when the step size is of 3 the beam diameter can still cover the pixels between the points of application. Hence this leads to a reduced amount of error. However, when the distance between the points of application increases beyond the FWHM, the error drastically increases; because the beam
diameter cannot encompass the entire pixels within the point of application. This leads to some part of pixels being not machined which adds to the total error produced at the end of the feature machining.

Table 4.3 Experimental Results (Uniform Depth Cavity)

<table>
<thead>
<tr>
<th>Setting</th>
<th>Step size</th>
<th>Error (nm^2)</th>
<th>Total machining time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.0067</td>
<td>259.00</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1,279,806.800</td>
<td>144.18</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1,683,202.610</td>
<td>69.37</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1,896.76</td>
<td>9.03</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>11,238.79</td>
<td>9.02</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>202,268.60</td>
<td>8.89</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>667,799.32</td>
<td>7.73</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>2,797.96</td>
<td>2.74</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5,036.75</td>
<td>2.74</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>12,559.04</td>
<td>2.73</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>122,442.31</td>
<td>2.72</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>411,951.52</td>
<td>2.60</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>4,214.300</td>
<td>0.562</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4,750.420</td>
<td>0.562</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6,834.690</td>
<td>0.561</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>10,182.340</td>
<td>0.560</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>14,810.020</td>
<td>0.560</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>49,248.610</td>
<td>0.560</td>
</tr>
</tbody>
</table>
The Table 4.3 represents the results obtained from the experiment of milling the uniform depth cavity. The Table 4.3 is similar to Table 4.2 where it represents the total error at the end of the completion of the iterative process, the threshold step size and the machining times for the corresponding step sizes for the specific beam setting. As it can be seen from the Table 4.3 the total error and the total machining time values are much larger as compared to Table 4.2 where the spherical lens of varying depth is being machined. This is due to the uniform depth that is being produced in the example 2, where as compared to example 1, a lot of material is removed. This explains the reason behind the large machining time values seen. Machining time values also depend on the number of pixels that are being actually machined. It bears a direct proportion between the number of pixels machined and the corresponding time. Also the amount of error produced is large which can be partly explained by the distance between the point of application and the beam diameter. Another reason for the large error is the large amount of material required to be removed from the substrate. The threshold step sizes are observed to be the same for the specific beam setting irrespective of the feature dimensions, complexity or shape being machined. This is because throughout the experimentation process, the dimensions of a single pixel on the substrate were kept constant at 6 nm. Also, the machine settings are constant for a specific machine (Helios 600 FIB/SEM). The threshold step size depends upon the beam diameter being employed and the dimension.
5. CONCLUSION

This research provides a pathway to eliminate the drawback of high operating cost and low processing efficiency encountered in the present nano-manufacturing methods or processes. The process proposed in the research, not only succeeds at increasing the processing efficiency, i.e. lower the machining time but also at the same time does not compromise on the quality of the product produced. The quality of the product produced if not better, is maintained at the current standards obtained by using the latest nano-manufacturing methods. Implementation of the process proposed in the research, will lead to a wide commercialization of a technology that has a bright future and which might become a part of our daily routine.

The research successfully achieved the object of lowering the processing time while maintaining the quality. The various analyses also provide information about factors that affect the machining process and which would provide valuable feedback for future course of action in the same field. The various factors like the beam overlap, the threshold step size, selection of the various step sizes and its corresponding effect on the quality of the product are all analyzed and concluded. Also the quadratic algorithm proposed by Sha et al., used for the iterative process is a special case application. However, the algorithm proposed in the research that intuitively explains how the original algorithm fails and how the new quadratic algorithm can be used for any application.

From the analyses of the threshold step size, for example 1 and example 2, it is observed that irrespective of the feature that is milled the threshold step size remains same for a specific setting. This is because the threshold step size is defined as the step size beyond which there is a sudden increase in the amount of error of the milled feature when
compared with the ideal feature. The threshold step size would change only if the dimensions for each pixel change. With a decrease in the individual pixel size, the threshold step size would increase. With an increase in the individual pixel size, the threshold step size would decrease. From the Table 4.2 and Table 4.3, it is observed that the total time for machining decreases as we increase the step size beyond the threshold step size, for any setting. However, the total machining time remains almost constant up to the threshold step size. This can be explained as, with the decrease in the number of decision variables (represented by the number of columns) the total number of operations also decreases. As a result the FIB machine has to operate on lesser number of pixels to achieve the targeted feature. But an important trade-off is required to be made, while trying to achieve higher processing efficiency and higher quality standards. This is because, increasing the step size beyond the threshold step size, to decrease the decision variables leads to larger amount of errors but, the machining time drastically reduces. While, on the other hand trying to maintain higher standards of quality the efficiency suffers. Hence, we could say that, for a specific setting, in order to achieve good efficiency and quality, the step sizes before the threshold could be employed depending upon the feature that is being milled. For features which require closer tolerances and higher finish a lower diameter beam could be employed. While, for features which do not have the necessary requirements of surface finish could be milled with larger beam diameters.

Another noticeable observation that can be made is that, the amount of error produced for the beams with smaller diameters for smaller step sizes is much higher as compared to beams with higher diameters, beyond the threshold step size. This can be explained by considering the beam overlap phenomenon, which depends upon the diameter
of the beam and the distance between the successive points of application of the ion beam on
the substrate.

Furthermore the flexibility of beam diameter can be incorporated within the
experiment so that the process would automatically select a larger beam at the initial stage
and then move to a beam with smaller diameter as the final stages of machining are reached.
This flexibility of removing larger amounts of material at the start and then smaller amounts
of material removal to achieve the required tolerances is known as the ‘coarse to fine’
approach. This flexibility would lead to even more reduction on time, as a larger beam
would initially remove large amount of material and then the smaller diameter beam could
be employed to achieve surface finish. The current research lacks this flexibility and
incorporating it could be one possible future course of action. Also, the research completed,
uses the raster scan to produce features on the substrate. The raster scan is a slow process
and hence a serpentine scan could be used. The difference in scanning is very small when
objects of nanosize are scanned, but in future saving one thousandth part of a second could
also lead to large economic savings. The serpentine scan is much quicker than raster scan
and also provides for more beam steering control when used for scanning larger objects.
Throughout the research process we have used the subtractive process for manufacturing.
However, the additive process which is based upon the BUM can also be incorporated to
achieve manufacturing of nanosized objects. These processes would not increase the
processing time considerably also, since the settling time for materials already deposited for
nanosized objects will be very small and can be neglected. As a result, the additive process
of manufacturing could also be a possible course of future action.
Thus the contribution of this research to the existing short body of knowledge is the novel idea of using a MATLAB code, coupled with a quadratic algorithm to achieve an increase in the processing efficiency and lowering the cost of the machining but at the same time maintaining the quality of the product.
function [columnIndex, rowIndex, objFunctn, locationData, coeffMatrix, idealObjFunctn, denominator, numerator, time, e] = myRowedited3(current, x, y, R, H, deltaX, deltaY, sigmaS, stepSize)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Formation of the columnIndex and rowIndex matrix%   deltaX, % deltaY,
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %

a = floor(((x)/deltaX));
b = floor(((y)/deltaY));
%deltaX = deltaY in nm%

halfWindowSize = ceil(3*sigmaS/deltaX);
windowSize = 2*halfWindowSize + 1;
% Image matrix

% Zero padding

zeroPad = floor(windowSize/2);
sizeX = a + 2*zeroPad;
sizeY = b + 2*zeroPad;

% Coordinates of elements of interest/machining

elemIntX = unique([zeroPad+1:stepSize:sizeX-zeroPad zeroPad+a]);
elemIntY = unique([zeroPad+1:stepSize:sizeY-zeroPad zeroPad+b]);

% Collection of all machining coordinates

elems = zeros(length(elemIntX)*length(elemIntY),2);
for m = 1:length(elemIntX)
    for n = 1:length(elemIntY)
        elems((m-1)*length(elemIntX)+n,:) = [elemIntX(m) elemIntY(n)];
    end
end

locationData = [(1:length(elems))' elems-zeroPad];

% Start location of window

windowLocationX = zeroPad + 1; windowLocationY = zeroPad + 1;

% Initializing a structure;
allData = [];

APPENDIX
windowPos = 0;
% m -> rows and n-> columns
for m = windowLocationX:sizeX-zeroPad
    allData(end+1).elems = [];
    allData(end+1).windowPos = [];
    for n = windowLocationY:sizeY-zeroPad
        windowPos = windowPos + 1;
        for p = 0:WindowSize-1
            pixelX = m-zeroPad+p;
            idx = find(elemIntX == pixelX);
            if (~isempty(idx))
                for q = 0:WindowSize-1
                    pixelY = n-zeroPad+q;
                    idy = find(elemIntY == pixelY);
                    if (~isempty(idy))
                        % This element should be processed
                        addElem = [elemIntX(idx) elemIntY(idy)];
                        % Coordinates of element to be processed
                        elemNo = find(sum((repmat(addElem,
                                    size(elems,1), 1) == elems),2) == 2);
                        allData(m-zeroPad).elems = [allData(m-zeroPad).elems elemNo];
                        allData(m-zeroPad).windowPos = [allData(m-zeroPad).windowPos windowPos];
                    end
                end
            end
        end
    end
end
allElems = []; rowIndex = []; allWindowPos = [];
for n = 1:length(allData)
    elemNo = allData(n).elems';
    allElems = [allElems; elemNo];
    rowIndex = [rowIndex; allData(n).windowPos'];
    allWindowPos = [allWindowPos; allData(n).windowPos'];
end

clear allData
columnIndex = allElems;
rowIndex';
allWindowPos;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Formation of the objective function matrix%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
\[ Ys = \frac{\text{current}}{(\pi \cdot 2 \cdot \text{sigmaS}^2)} \cdot 0.27 \cdot 10^9; \]

```plaintext
dataVals(a*b) = struct('value', []);

for m = 1:length(unique(allWindowPos))
    idx = find(allWindowPos == m);
    xi = mod(m,a);
    if xi == 0
        xi = b;
    end
    yi = ceil(m/b);
    for n = 1:length(idx)
        elementNo = columnIndex(idx(n));
        xj = locationData(elementNo,3);
        yj = locationData(elementNo,2);
        value = Ys*exp(-((xi-xj)*deltaX).^2+((yi-yj)*deltaY).^2/2.*sigmaS^2));
        dataVals(m).value = [dataVals(m).value value];
    end
end
C = [dataVals.value];
objFunctn = C';
```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Formation of the sparse matrix%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
coeffMatrix = sparse(rowIndex, columnIndex, objFunctn);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Formation of the ideal objective function matrix%  
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
idealObjFunctn = zeros(a*b,1);
for j = 1 : 1 : a
    for i = 1: 1: b
        index_ij = (j-1)*a + i;
        index_i = ((i-a/2)-0.5)*deltaX;
        index_j = ((j-b/2)-0.5)*deltaY;
        idealObjFunctn(index_ij,1) = H -(sqrt((R^2-index_i^2-index_j^2)));  
    end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Iterative process%
```
denominator = transpose(coeffMatrix)*coeffMatrix;
numerator = -transpose(coeffMatrix)*idealObjFunctn;
v = ones(length(elemIntX)*length(elemIntY),1);
v1 = ones(length(elemIntX)*length(elemIntY),1);
error = sum(abs(v1-v));
tol = 0.000001;
e=[];
while error >= tol
  v1 = ((max(-numerator,0))./(denominator*v)).*v;
  error = sum(abs(v1-v));
e=[e error];
if error >= tol
  v = v1;
end
end

time = v1;
BIBLIOGRAPHY


VITA

The author, Sushrut S. Naik, was born in a small town Bhusawal in the western state of Maharashtra, India in 1988. He successfully completed his schooling from Nashik, India and then received his Bachelor in Mechanical Engineering from University of Pune, Maharashtra, India. During his completion of the requirements for Bachelor in Mechanical Engineering, the author was employed as an Engineering intern with TATA Motors, Pune, India. There he successfully completed projects and submitted a report entitled "Design and modification of the angular grinding wheel head assembly." The project saved the company approximately Rs.0.3 million annually in service and maintenance. He was also a part of the prestigious National event winning badminton team. The author has also completed a certificate in German and French languages, from the University of Pune.

In August 2010, he joined the Master of Science program in Engineering Management at Missouri University of Science and Technology, Rolla USA. His research work under Dr. Qin mainly focused on obtaining an optimized solution for the focused ion beam nano-manufacturing process, with the objective to increase the processing efficiency and at the same time maintaining the quality of the product produced. The author also handled the post of Treasurer efficiently and diligently of Council of Graduate Students (CGS) for the academic year 2011-2012. The author received his Master of Science in Engineering Management from Missouri University of Science and Technology, Rolla in May 2012.