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## RLSM: REMOTE EXCIMER LASER MICRO-MACHINING SERVICES MODEL

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## ABSTRACT

In this paper, we discuss an Internet based excimer-laser-micro-machining services model that allows multiple users to collaboratively design and fabricate laser micro-machining features. This model implements the client - server architecture to support design and editing of features by multiple clients. The client side needs minimum software installation and is made intelligent by incorporating feature verification algorithms to ensure speed and efficiency of the design process. The server side supports solid modeling, solving of geometric constraints, data management and synchronization of clients. JSDT Interface links the server and the client sides. The remote laser micro-machining services model (RLSM) provides a collection of laser micro-machining features such as through-cuts, channels and pockets and different polymer materials such as PMMA, Kapton, PET and Uplex for the user to choose from.

In developing this services model we provide a distributed collaborative architecture that incorporates the manufacturing constraints of laser micro-machining in the design stage. The remote service center operation is further integrated with automated path generation for laser micro-machining of the features. To our knowledge this the first attempt towards developing a collaborative environment for design and manufacturing of MEMS components. The importance of such a model in the manufacturing arena of the 21st century is also discussed.

**KEY WORDS**
Collaborative manufacturing, Excimer laser micro-machining, Micropump fabrication.

## 1. INTRODUCTION

In the 21st century that has marked an ever-increasing product intricacy levels and demand for shorter product manufacturing cycles along with higher product quality and life-time, the idea of a monolithic organization with one centralized corporate may fade [1]. These factors demand a new manufacturing paradigm in which companies specialized in different areas collaborate for meeting the customer requirements. Different internet based manufacturing models have been suggested for collaborative manufacturing such as the telemanufacturing model [2], Cocadcam [3], and Cyber-cut software [4]. In the telemanufacturing model [2] different companies handle different aspects of product manufacturing such as marketing, product design, fabrication and delivery. Each of these ports called a Service Expert Center (SEC) possesses the state of the art technologies in the respective field. The other major component in this model is the In-house-controller (IHC) that comprises of an in-house team integrating the different SEC s. Such a model offers flexibility and has advantages such as allowing limited investment in equipment and hardware, providing flexibility in changing the service providers and keeping abreast with the latest technical developments through the SEC s. Kao et al. [3] developed a collaborative CAD/CAM application 'Cocadcam' that allows co-editing of geometry by designers at distributed locations. In this application, a traditional CAD/CAM system has been extended into a multi-client application through the implementation of communication and network strategies that include UNIX inter-process communications (IPC) and a connection oriented client and server (COCS) model. 'Cocadcam' develops an NC code on the collaboratively discussed geometry for milling operations. The main drawback with this system is the need for a CAD/CAM software at each client. Ahn et al. [4] developed 'CyberCut' software that made use of a proprietary web-based Java CAD tool called 'WebCAD' for coupling the entire concept to the fabrication pipeline for 3-axis milling. This approach obviated the need for integration with any legacy code and provided the platform for automating the manufacturing process. Jiang et al. [5] developed an e-services model for fast collaborative product design on the internet and fabrication by rapid prototyping.

Attempts towards collaborative product design on the Internet include the CollIDe system [6], CyberEye [7], Collaborative Solid Modeling (CSM) [8]. CollIDE system is a shared 3D workspace that can be accessed by multiple users. This system can be coupled with conventional single user CAD systems and it supports real-time object data exchange, synchronized 3D camera view and multiple user interactions. CollIDE also allows the user to transfer geometry from the private stage to the shared stage [6]. CyberEye is another web-based environment that is used to support collaborative design in multidisciplinary team based engineering. It comprises of three modules: Product Visualization Module (PVM), Product Information Module (PIM), and Team Management Module (TMM) that handle the different processes involved in the collaborative design process [7]. Collaborative Solid Modeling (CSM) allows sharing and editing of a solid model over the web synchronously. However, it requires a solid modeler at each client [8].

Thus extensive research is taking place in the twin fields of collaborative design and collaborative manufacturing. But almost all the work done so far is concentrated upon product manufacturing using conventional manufacturing techniques. In this paper, we present a remote services model for excimer laser micro-machining.

## 2. IMPORTANCE OF LASER BASED MICRO-MANUFACTURING TECHNIQUES

During the last decade there has been tremendous progress in MEMS research and the micro/nano-industry is presently estimated to be a multi-billion dollar sector. Different micro-fabrication techniques such as the silicon based IC-fabrication techniques; laser based micro and nano-machining techniques are being developed for such applications. Of these, the laser based techniques allow greater material versatility and faster prototype generation. Among the different lasers available, the pulsed lasers are preferred in MEMS applications owing to their superior machining quality, higher resolution, higher speed of processing and better surface finish. Compared to photolithography process that requires many steps, pulsed laser micro-machining (PLMM) involves just one machining step and hence for prototype fabrication in the micron dimensions, PLMM is cost effective. Excimer lasers belong to the family of pulsed laser micro-machining systems. The energy of the excimer lasers pulses is in the range of the bond energies of polymers and hence these lasers are best suited for polymer micro-machining. Excimer lasers are used in different applications such as for machining channels, grooves and reservoirs in polymers for microfluidics applications, in sub-micron lithography, in electronic packaging industry, in fabricating micro-sensors and micro-actuators [9, 10, 11, 12, 13].

## 3. COLLABORATIVE ENVIRONMENT FOR EXCIMER LASER MICRO-MACHINING

To the best of our knowledge, this is the first study that facilitates design and manufacturing of MEMS components in a collaborative environment. The remote laser micro-machining services model (RLSM) developed in this work is based on a design for manufacturability paradigm and thus ensures manufacturability of the designed features. The utility of our model is demonstrated by fabricating microsystems such as flow regulating channels and micropumps that are some of the key components in the microfluidics industry [14, 15, 16].

The overall vision of this work is to build a software architecture that supports the flow of information between clients, vendors and experts involved in varied domains of activities related to the micro-machining process. The collaborative environment facilitates a synergistic relationship between the different users. Thus a remote user would not only be able to design parts in a design-for-manufacturing (DFM) environment but also will be able to gain access to the expertise available in the manufacturing, design, packaging and other sectors. Such a software architecture also enhances the efficacy of a design expert or marketing strategist in assisting others during entire product design and development.

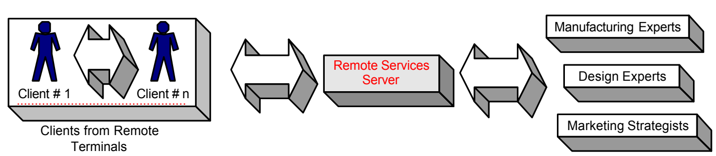


Figure 1: Distributed Manufacturing Model

## 4. RLSM ARCHITECTURE

The remote laser micro-machining services model (RLSM) is based on a three-tier architecture namely the server side, the client side and the database. The overall architecture is as shown in Figure 2.

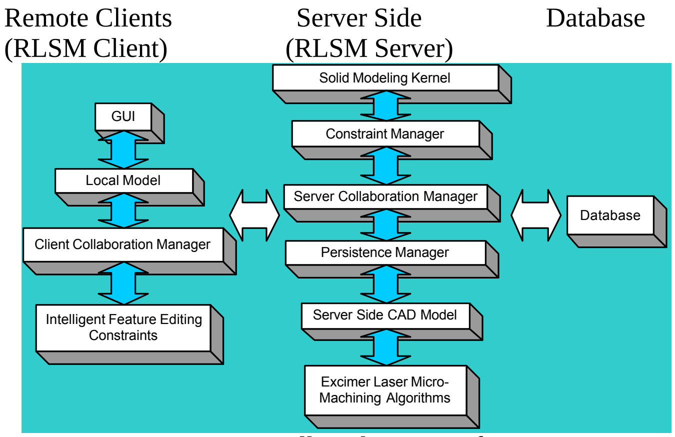



Figure 2: Overall Architecture of RLSM

#### 4.1 RLSM CLIENT SIDE

The RLSM client side consists of different modules such as the GUI, the local CAD model, the client collaboration manager and the intelligent feature editing constraints. It is based on a model-view-controller pattern. The 'model' object represents the CAD model on the client side and manages the behavior and data of the application domain, responds to requests for information about the CAD model and to instructions to change the state of the CAD model. The 'view' object manages the graphical and textual display of the CAD model on the client side. The 'controller' object consists of the GUI and the client collaboration manager. It interprets the mouse and keyboard actions from the user and instructs the view to change accordingly. The Client Collaboration Manager module receives commands from the server and edits the client side CAD model accordingly. The intelligent feature editing constraints module incorporates intelligence on the client side. These constraints allow the user to design features in accordance with manufacturing limitations and thus ensure the design for manufacturability (DFM) paradigm.

#### 4.2 DATA STORAGE ON THE CLIENT SIDE

The information from the user is received through the GUI module and stored in an object of the 'ClientProduct' class. The remote laser micro-machining services model (RLSM) currently supports three types of laser micro-machining features namely through-cuts, channels and pockets. These features are as shown in Figure 3. The user input consists of the geometry and manufacturing related information for these three kinds of features. The UML diagram of the 'ClientProduct' class is as shown in Figure 4. The geometry related information of the features is stored in an object of the 'ClientSketchModel' class and the manufacturing related information is stored in variables such as the 'featureType' and so on. On the server side, an identical class is defined called the 'ServerProduct'. The objects of this class are updated through command objects sent from the client side.

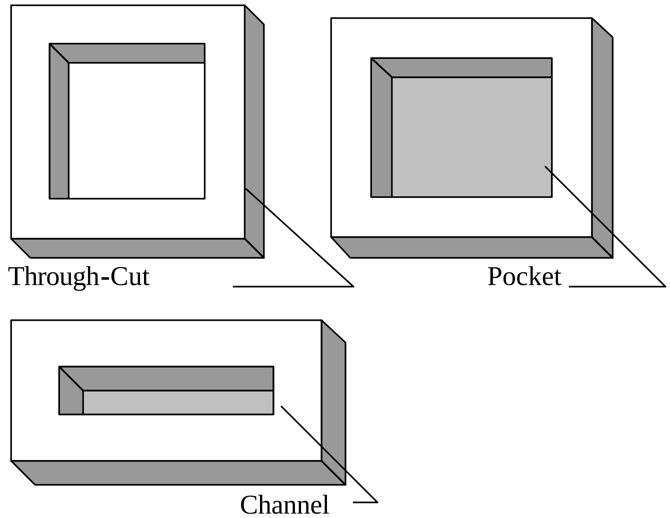



Figure 3: Laser based micro-machining features

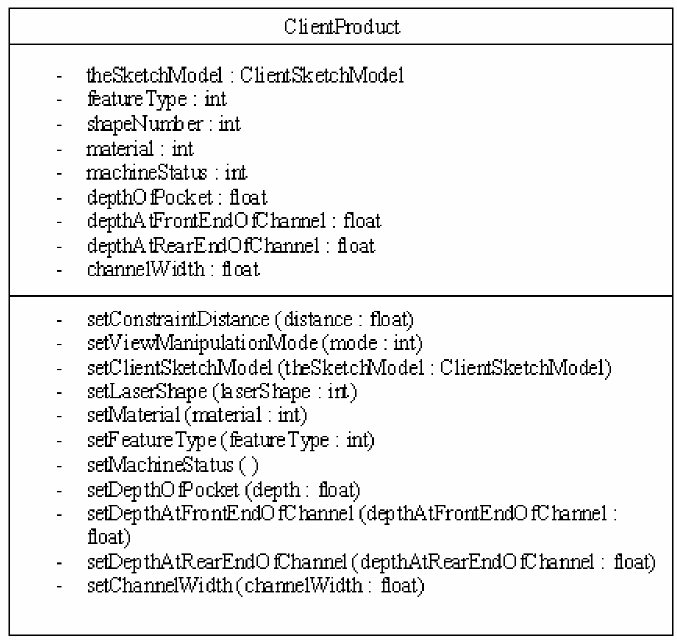



Figure 4: UML Diagram of the Client Product class

#### 4.3 DATA TRANSFER FROM THE CLIENT TO THE SERVER

The user input is stored on the server side in the 'ServerProduct' class. The data flow from the client to the server is as shown in Figure 5. The 'Client-Collaboration-Manager' module sends the command objects corresponding to every user input to the server. These command objects are received by the 'Server-Collaboration-Manager' module on the server side and when executed initialize the 'ServerProduct' class object.

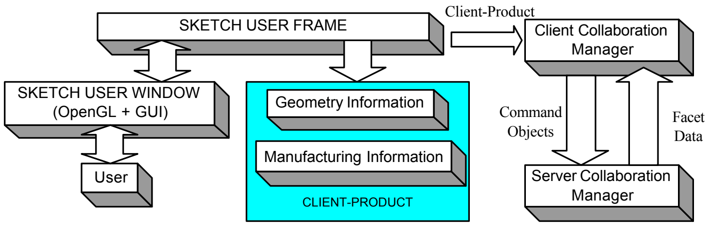



Figure 5: Data flow from the client to the server

### 4.4 RLSM SERVER SIDE

The RLSM server side contains different modules such as the solid modeling kernel, the constraint manager, the server collaboration manager, the persistence manager and the excimer laser micro-machining algorithms. The solid modeling kernel (ACIS) module is used to create 3D models of the features to be sent back to the client side for visualization purposes. Java Native Interface (JNI) methods are implemented for accessing the ACIS software through Java and the created ACIS solids are faceted and sent back to the clients. Faceting operation decreases the memory required for representing the 3D feature and thus leads to faster data transfer rates over the internet. The constraint solver module allows the clients to impose geometric constraints on the model and edit the model accordingly. The server collaboration manager module coordinates the data flow between the server and the clients. The persistence manager module saves and retrieves the data from the database. Finally the excimer laser micro-machining algorithms module consists of C++ programs that extract the machining path required for manufacturing the features. These algorithms also create 3D models of the machined feature, which are faceted and sent back to the client.

### 4.5 MACHINING INFORMATION EXTRACTION AND PROCESSING

The excimer laser micro-machining algorithms are activated upon pressing the 'LaserMachine' button present in the GUI on the client side. This operation sends the 'laser-micro-machining' command object to the server side which when executed does the following operations:

(1) Extracts the array of features present in the 'ServerProduct' class object.
(2) Extract the geometry and manufacturing related information of each feature.
(3) Create and initialize the corresponding java-based micro-machining feature objects.
(4) Execute the C++ laser micro-machining algorithms through the JNI interface.
(5) And finally store the faceted model of the micro-machined features that are returned by the JNI methods.

### 4.6 PATH EXTRACTION AND 3D MODEL CREATION FROM MICRO-MACHINING OBJECTS USING JNI METHODS

The JNI interface creates an array of C++ micro-machining objects from the corresponding array of java based micro-machining objects. The UML diagram of the C++ feature object class is as shown in Figure 6. The methods such as 'createPath' and 'create3DView' of the C++ feature object perform functions such as extracting the micro-machining path and creating a 3D ACIS model of the machined feature. This 3D solid model is faceted and is sent back to the client side for visualization purposes. The data flow from the server to the client is shown in Figure 7.

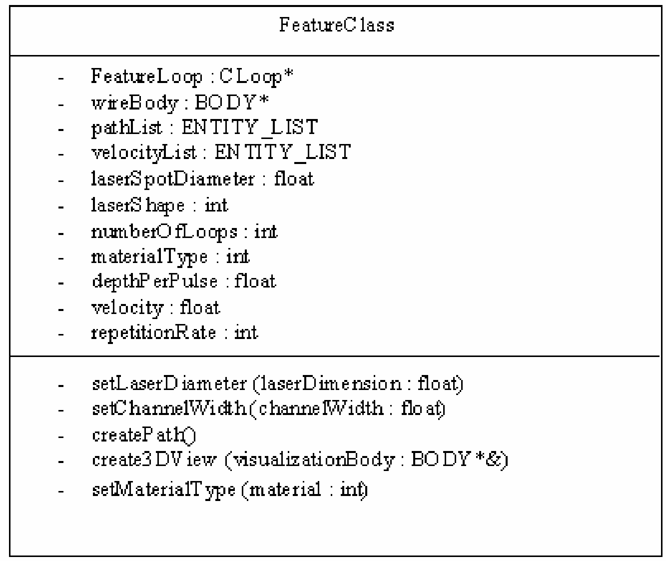



Figure 6: UML Diagram of C++ Feature object

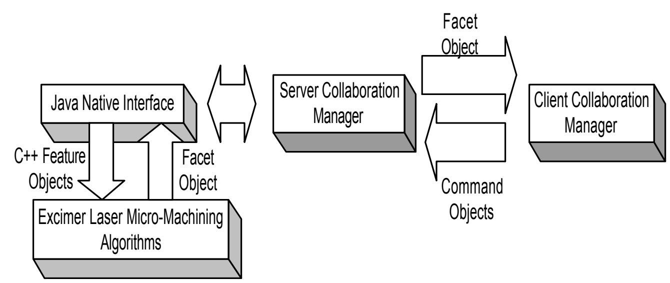



Figure 7: Data flow from the server to the client

### 5. WEB-BASED USER INTERACTIONS FROM A REMOTE TERMINAL

The user can access the collaborative environment through the internet by installing the Java SDK software and the magician classes in the remote computer. The user interaction for creating a through-cut feature is described below.

### CREATING A THROUGH-CUT FEATURE

In Figure 8 the sketch panel is shown in which the user can create and edit the geometry for creating a through-cut feature. Figure 9 shows an example of a closed-loop-geometry that the user can draw and the different dialog boxes that the user can access by using the appropriate buttons for entering manufacturing related information such as the material information, the information upon the laser spot shape and the type of the feature. Figure 10 shows the 3D faceted model of the machined feature.

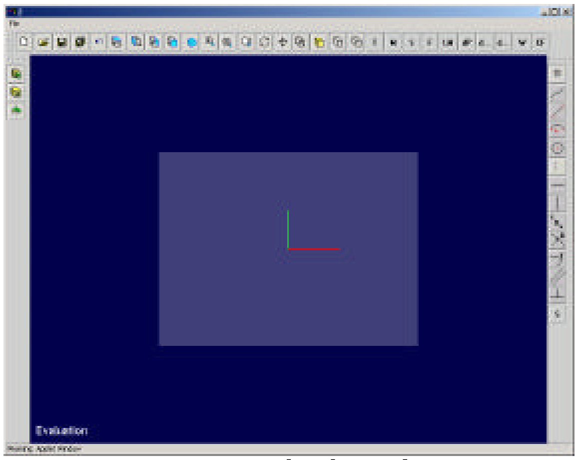



Figure 8: Sketch Panel

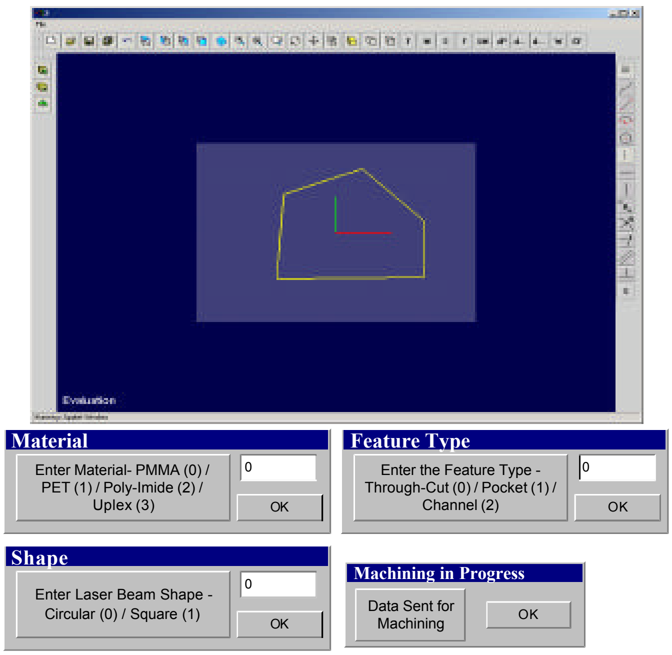



Figure 9: Closed loop drawn by the User and the various dialog boxes

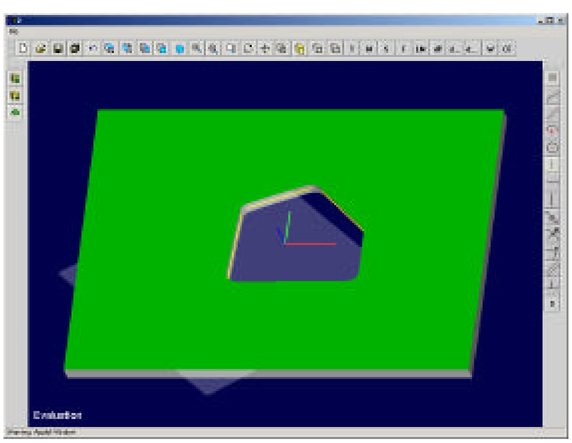



Figure 10: 3D Final Product Model

The other features namely Channels and Pockets can be designed and fabricated in a similar manner. For machining Channels additional information in terms of the width of the channel and the depth at the two ends of the channel also need to be provided by the user. For machining a Pocket the user input includes the depth of the pocket.

## 6. EXPERIMENTAL SETUP

### 6.1 SCHEMATIC AND SAMPLE MOTION

The mask projection technique is employed for excimer laser micro-machining. The properties of the excimer laser such as low beam divergence and high spatial incoherence makes it suitable for machining materials using the mask projection technique. Krypton-Fluoride excimer laser ($\lambda$ = 248 nm) is used for our experiments. The setup is shown in Figure 11. The mask used in our experiments comprises of an aperture that is either circular or square in shape. It is projected onto the sample at a fixed demagnification of 10. The typical aperture sizes used are 300 μm, 500 μm and 1000 μm for square shaped apertures and 400 μm, 600 μm and 3500 μm for circular apertures. A computer-controlled shutter allows automatic switching of the laser. The entire machining process is monitored using a CCD camera and a display. The machining parameters are the repetition rate or the number of pulses that hit the sample per second, the velocity of traverse of the sample, the laser beam diameter and the fluence level of the laser beam. In our experiments, the repetition rate is set at 5 Hz; the fluence of the laser beam (the power density of the beam) is set to 1.60 J/cm$^2$. The sample is mounted on high precision motion stages manufactured by Micos Inc. The x-y stages have a resolution of 0.1 μm. The maximum travel distance in the x and y directions is 200 mm and the maximum speed equals 60 mm/s. The minimum speed of the stages is 0.1 μm/s.

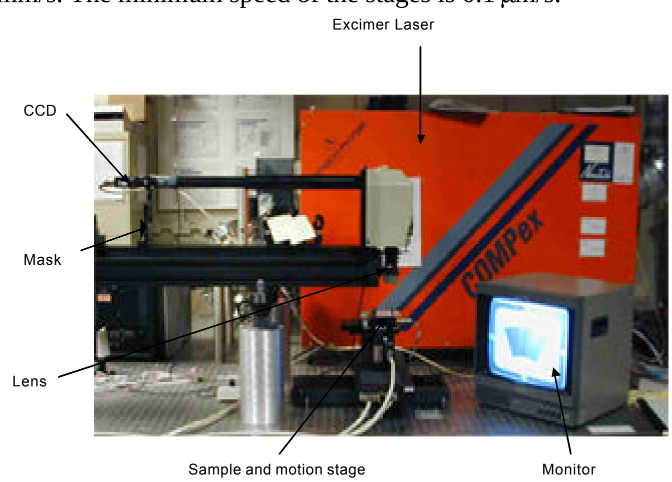



Figure 11: Experiment Setup

### 6.2 MATERIAL CHARACTERISTICS

Different types of polymers such as PMMA, Kapton, Uplex and PET can be machined using the remote laser micro-machining services model architecture. The depths of cut per pulse at the fluence of 1.60 J/cm$^2$ are measured for each of the polymers and the results are tabulated as shown in Table 1. From the table, it can be seen that PMMA takes the shortest time and Uplex the longest.

Table 1: Depth of Cut per pulse at Fluence = 1.60 J/$cm^2$

| Material | Depth of cut per pulse at a Fluence = 1.60 J/$cm^2$ in microns |
|---|---|
| PMMA | 1.816 |
| PET | 0.804 |
| Kapton | 0.608 |
| Uplex | 0.568 |

## 7. PATH ALGORITHMS FOR EXCIMER LASER MICRO-MACHINING

The following sections provide a detailed overview of the path planning algorithms.

### 7.1 THROUGH-CUTS

For through-cuts, the machining path is an offset of the closed loop of lines and arcs by a distance equal to the half the laser spot dimension. The software presently supports square and circular laser spot shapes. In case of a square spot the offset distance is equal to half the length of the square spot on the polymer surface. In case of a circular spot, the offset distance is equal to the laser spot radius. For a polymer film thickness = d, depth of cut per pulse = dPP, repetition rate = n Hz and a beam spot size = D, the velocity of traverse of the beam is

V = D*n*dPP/d

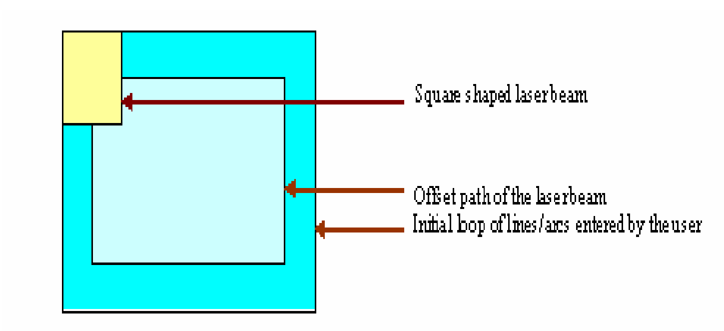



Figure 12: Through-cut machining path

### 7.2 POCKETS

In case of pockets, different paths were implemented including the zigzag motion and motion in both the x and y – directions. Such motions created a wavy surface due to the offset between two successive scan lengths. This waviness was minimized by decreasing the laser spot diameter and increasing the scan speed.

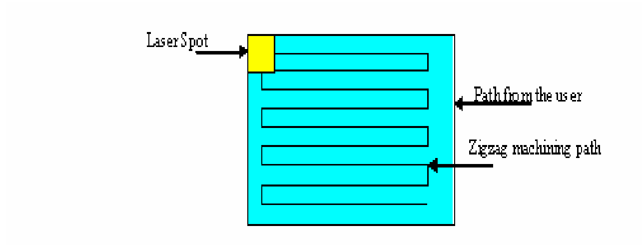



Figure 13: Zigzag laser machining path for a Pocket feature

### 7.3 CHANNELS

In case of channels, the machining path is either along a line or an arc that defines the length of the channel. In case of constant depth channels, the velocity of traverse is given by

V = D*n*dPP/d where d equals the depth of the channel and the other parameters are the same as those for through-cut features.

In case of varying depth channels, the channel length is discretized into a set of points and the laser traverse velocity is adjusted such that the depth at the next point gets machined by the time the laser beam trailing edge moves past that point.

Velocity of traverse = $\Delta$x*n*dPP/z [i+1] where z [i+1] is the depth at the next point and $\Delta$x is the distance between two successive points.

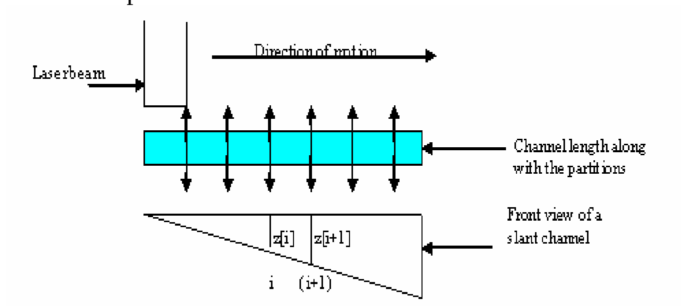



Figure 14: Machining path for a tapered channel

### 7.4 INTELLIGENT CLIENT IMPLEMENTATION

The manufacturability of a feature is decided by the available laser spot sizes and shapes, limitations in precise sample motion over long distances and finally upon the range of energy levels of the laser beam available for micro-machining. In our case the restriction imposed by the laser spot is found to be the most critical factor. Hence intelligence is incorporated on the client side for checking the feasibility for machining a feature with the given set of available laser spot shapes and sizes.

In case of through-cut and pocket features, the laser spot diameter is determined by the shortest edge of the feature. The minimum length of the edge that can be machined is set to 50 µm. Thus if the length of the shortest edge in the loop is less than 50 µm the user would be prompted to change it.

In case of channels, the laser spot diameter is determined by the width of the channel. The minimum width is again restricted by the minimum available laser spot diameter. This is set to 30 µm.

The following figures show the different dialog boxes displayed. The user is prompted for feature verification. The results are displayed accordingly.

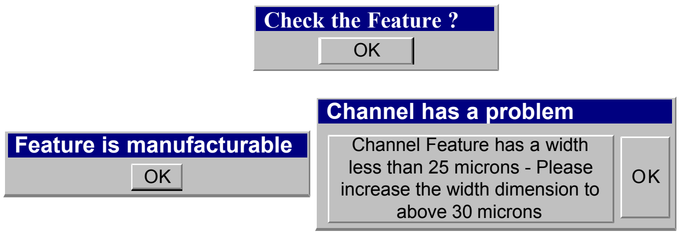


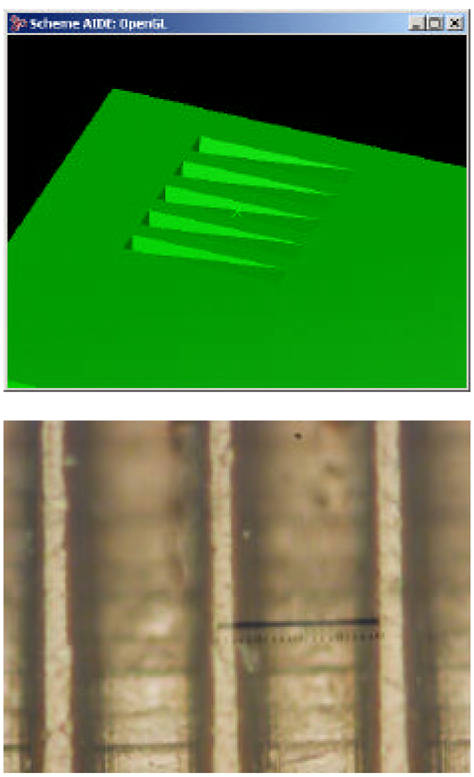

Figure 15: Feature Verification Dialogues

## 8. EXPERIMENTAL RESULTS

Some of the experimental results obtained by using the remote services model for excimer laser micro-machining are discussed below.

### 8.1 TAPERED CHANNELS

Tapered channels are used in microfluidics as flow regulating devices. An array of these channels is machined in Uplex polymer. The array consists of tapered channels of length = 300 µm with taper from 0 µm at one end to 36 µm at the other and the width of the channel = 50 µm. The offset between two successive tapers is equal to 30 µm. For each channel, the laser beam diameter is set to the width of the channel = 50 µm. The experiment result and the 3D faceted model created using ACIS are as shown in Figure 16.

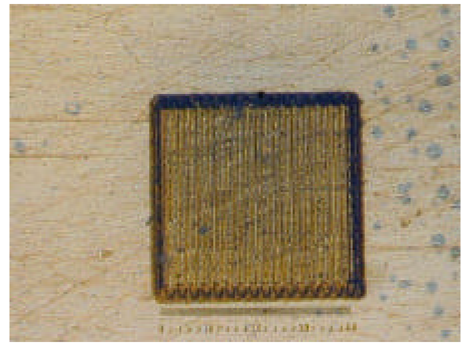



Scale: 1 division = 25 µm

Figure 16: ACIS software output and experimental result for an array of tapered channels

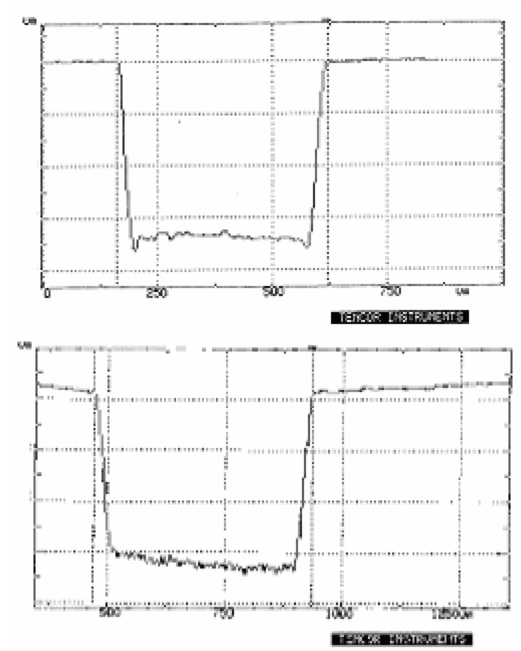
### 8.2 POCKETS

Pocket machined in Kapton is shown in Figure 17. The length and width of the pocket is 400*400 µm and the laser beam diameter used for machining the pocket is 20 µm. The profilometer scans in the x and y –directions are shown in Figure 18. The surface roughness of the machined pocket is around 2 µm.



Scale: 1 division = 20 µm

Figure 17: Pocket machined in Kapton




Scale: x-axis 1 unit = 125 µm, y-axis 1unit = 2 µm

Figure 18: Profilometer Scans along the x and y-directions

### 8.3 MICROPUMP

We machined a valveless diffuser micropump in Kapton. The different sections of the micropump are the chamber, the diffuser channels and the reservoirs. The schematic of the micropump is shown in Figure 19.

I. Chamber: The chamber is the central portion of the micropump with a diameter of 6250 µm. The flexibility of the chamber directly affects the flow rate of the fluid across the pump. The larger the deflection of the chamber diaphragm, the higher the flow rate. Because the pump is made using polymers, and the polymer film deflects much more than a conventional silicon diaphragm, therefore the pumping rate also is higher than that of a silicon based micropump.

II. Diffuser Channels: As the diaphragm covering the chamber of the micropump is actuated, the fluid gets pumped from the inlet to the outlet because of the diffusers. As the diaphragm moves up, the pressure gradient in the right diffuser becomes higher than the pressure gradient in the left diffuser. As a result more fluid enters the chamber from the left side. As the diaphragm moves down, the pressure gradient in the left diffuser becomes greater than that in the right diffuser. Therefore, more fluid moves out of the right diffuser than that from the left. Thus the effective pumping direction is from left to right. The diffuser design is very critical for an efficient performance of the pump. In our case, the different dimensions used are slight variations of the dimensions found in the literature. The diffusers channels have diameters of 40 μm and 400 μm at the two ends and a length of 2250 μm.

III. Reservoir: The inlet reservoir is connected to a source of the fluid being pumped. The outlet reservoir is connected to the sink. The reservoirs have a diameter of 3125 μm each.

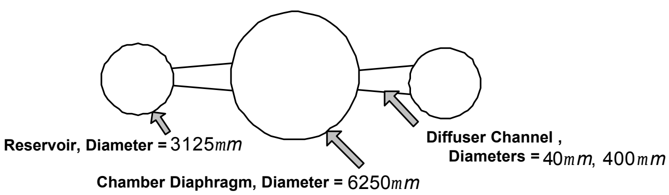



Figure 19: Schematic of Micropump

### 8.3.1 FABRICATION PROCEDURE

For fabricating the pump, two different laser spot sizes – 360 μm and 30 μm are used. This is because of the large variance in size between the chamber and the diffuser sections. The fabrication involved machining the chamber and reservoirs first using the larger mask and then switching to the smaller mask for machining the diffuser channels. The shutter has been operated for blocking the laser while moving from one end to another during the machining process and also while changing the masks. The machining path file from the program had all the commands for executing the operations like setting the required velocity for motion, closing the shutter during the non-machining mode when the sample is being positioned under the laser and also while changing the masks and opening the shutter during the machining process.

### 8.3.2 SOFTWARE OUTPUT AND THE FABRICATED MICROPUMP

The faceted model of the micropump that is sent back to the user is shown in Figure 20. The fabricate micropump is shows in Figure 21. The faceted model provides an unambiguous feedback to the user of the final expected product and thus facilitates quicker design iterations.

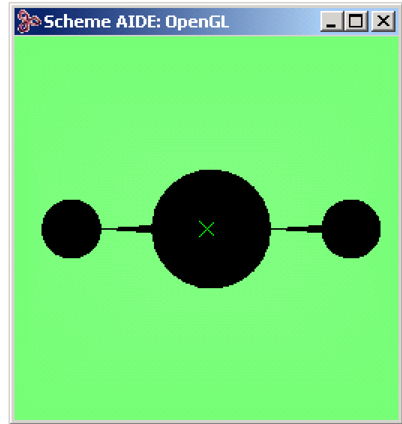
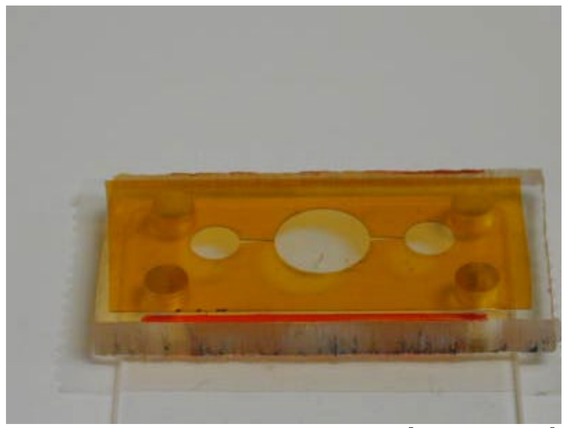



Figure 20: ACIS Output



Scale: 1 inch

Figure 21: Fabricated Micropump

## 9. CONCLUSIONS

In this work we developed a software architecture for web-based excimer laser micro-machining. The software enables collaborative design and fabrication of excimer laser micro-machining features such as through-cuts, channels and pockets in different types of polymers such as PMMA, Kapton, PET and Uplex. We successfully demonstrated the manufacturing of MEMS components through the machining of some key components for microfluidics applications.

The main contribution of this work is in providing a collaborative environment for excimer laser micro-machining. To the best of our knowledge this is the first study in applying collaborative manufacturing schemes to micro-machining processes. The software architecture provides a common platform for smooth flow of information between people from different domains of activities related to the micro-manufacturing process. The issues related to information security need to be addressed in the future.

This work also serves in making MEMS technologies easily available. Laser based fabrication of MEMS systems is one of the cheapest ways for prototype and small batch micro-manufacturing. In these areas laser micro-machining outruns the standard IC fabrication processes. This work opens the doors for consumers to avail such high precision technologies from remote places for fabricating prototypes in an inexpensive and versatile manner.

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