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Design and Control of Laser Micromachining Workstation

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***Abstract*—The production process of miniature devices and microsystems requires the utilization of nonconventional micromachining techniques. In the past few decades laser micromachining has became micromanufacturing technique of choice for many industrial and research applications. This paper discusses the design of motion control system for a laser micromachining workstation with particulars about automatic focusing and control of work platform used in the workstation. The automatic focusing is solved in a sliding mode optimization framework and preview controller is used to control the motion platform. Experimental results of both motion control and actual laser micromachining are presented.**

I. Introduction

In the past few decades laser micromachining has became an important micromanufacturing technique for many industrial and research applications. The popularity of this technique is growing with the increasing need for non contact machining. Non contact machining offers many advantages over conventional machining such as absence of tool wear problem, absence of thermal distortions in machine tools and deflection of the tool under machining forces. Unique characteristic of the laser micromachining is the possibility of etching or ablating exceptionally small features in many different materials with minimal damage done to the non irradiated regions of the material [1 - 3].

Researchers and authors have dedicated much attention to the laser micromachining process modeling, simulation and applications to variety of materials [4-11]. However not much literature is present about the design approach and description of the overall laser micromachining workstation. In [12] authors present the laser micromachining system for flat panel display repair. The design of mechanically decoupled type dual motion stage is described and control techniques for such stage are discussed in detail. Authors dedicate very little attention to the description of the overall system configuration. In [13] laser micromachining system that can be used for applications in the electronic and microfabrication industry is presented. Performance parameters are discussed in detail. System features femtosecond pulsed laser and acousto-optic deflectors as actuators for positioning of scanning mirrors. Many technical issues and details concerning the design of the direct writing laser lithography system are discussed in [14]. Authors present a low-cost direct writing laser lithography system featuring fixed optical beam. Realization of nanosecond laser micromachining system consisting of laser, mechanical and optical structure and control system is presented in [15]. This work gives moderately detailed description of the workstation and focuses on the nanosecond pulse laser fabrication process parameters optimization.

In this paper the design of laser micromachining workstation as a laboratory set-up aimed for further investigation of both the control and the process is presented. Firstly it deals with the design and implementation of the workstation, control for high precision motion stage and the automatic focusing of the laser beam is discussed. The experimental results are shown to verify the achieved results. Further work is mentioned at the end.

The paper is organized as follows; in Section II detailed descriptions of the laser micromachining workstation is given. Section III discusses the trajectory generation and control method for the precise motion stage. Experimental and simulation results are given in the Section IV. Section V contains conclusion and final comments.

II. Laser Micromachining Workstation

The design approach for a laser micromachining workstation (LMW) is guided by the needs of using it as a laboratory tool. Our goal has been to design a modular system for easy customization and flexibility of the experimenting with different functions of the system. Currently the LMW is equipped with a motion platform that allows micromachining of the planar structures only. Due to the modular design approach, micromachining of the structures on the platforms that have different kinematical configurations can be easily done by interchanging the current motion platform with the platform that provides more degrees of freedom in the required workspace.

Workstation is composed of 5 modules; mechanical structure, laser source, beam delivery optics, 3 axis precise motion module and control hardware and software. The conceptual relationship between these modules is depicted in Fig. 1.

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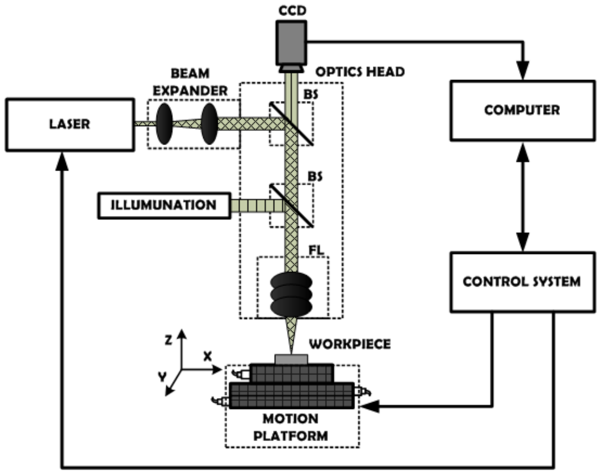


Fig. 1. Conceptual relationship between modules of LMW

A. Overall Structure

Integration of complex and demanding modules needed for proper operation of a laser micromachining workstation requires the design of mechanical support structure that contains all other modules of the workstation. The mechanical structure of laser micromachining workstation consists of machine base and column, optics head lift mechanism, planar x-y positioning stage and positioning stage translation mechanism. The optics head is fixed via two brackets with respect to stationary columns. The head is driven in vertical direction via actuators located in the base of the workstation.

The positioning stage translation mechanism is designed to allow the system operator insertion and fixing of the workpiece onto holder in an ergonomic fashion. The planar x-y positioning stage is fixed on a movable plate which allows the user to automatically move it to a position at which material can be loaded or the finished micromachined workpiece removed.

The beam delivery optics is necessary module of the laser micromachining workstation that serves the purpose of focusing the laser beam to a tiny beam waist diameter and in turn increases the energy density of the laser beam. The workstation features Haas LTI laser micromachining fine cutting head [16]. The internal optical structure of the beam delivery system can be understood from the Fig. 1, it consists of 2 beam splitters (BS) to incorporate the illumination light and on-axis camera (CCD) vision into the same path as laser light. Approximated final waist diameter of the laser beam is 10.8 μm and depth of focus is approximately 54 μm.

Laser generation system consists of beam generation unit, internal laser controller and beam delivery cord. Laser beam is generated by red ENERGY G3 HS series 20W, 1065nm wavelength pulsed fiber laser supplied by SPI Lasers [17].

B. Control Software

Laser micromachining system has to meet requirements such as the ability to alter various process parameters, namely, laser, material and motion parameters so investigation of material science phenomena or micromachining phenomena is possible. System controller and software of the laser micromachining workstation have many objectives and they could be classified as follows:

- Accurate positioning of the workpiece.
- Reliable and fast tuning of the laser parameters.
- Part positioning and laser pulses synchronization.
- User-Machine interface.
- Overall monitoring and control of auxiliary devices.

Currently workstation is controlled by the dSspace control system $DS1005$ that features a PowerPC $750GX$ processor running at $1GHz$ and DA/AD, position encoder and digital I/O cards. This control system is used for the first prototype development and will not be used in the final version of the workstation mainly due to the economical considerations. Workstation also features the central computer that runs on Windows XP.

Currently only $2D$ technical drawings are accepted by the software. User inputs the technical drawing in $.dxf$ format generated by the technical drawing program such as $SolidWorks$.

C. Precise Planar Motion Stage

Motion stages providing the motion in planar, x-y, plane are designed using brushless, high-precision direct drive linear servomotors. The absence of iron in the forcer or shaft results in the ultra high precision and very low cogging force. Each stage incorporates the position measurement in the mechanical structure. Position feedback is obtained from a high grade analog optical encoder in conjunction with an efficient interpolator. Optical encoder provides position measurement with 10 nm resolution. In addition to the drive mechanism and position sensor, roller cage linear slides are used to provide linear motion. These linear slides are designed specifically for highest accuracy requirements and have very low friction force. Specifications of the precise motion stage are given in the Table 1.

III. LMW Motion Control

In order to perform laser micromachining, the geometrical features of the part to be machined have to be designed and technical drawing must be supplied to the software. Technical drawing is supplied in .dxf format file [18].

In order to assure perfect replication of the part specified in technical drawing and achieve high quality laser micromachining, trajectory generation algorithm results should guaranty smooth position, velocity and acceleration transitions. Jerky motion and position overshoot at the corner points should be minimized or completely avoided in order to guaranty high quality laser micromachining.

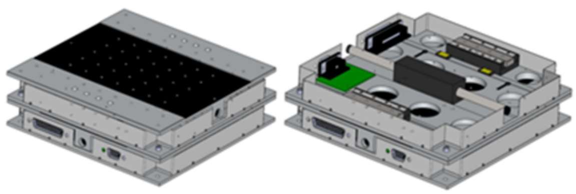


Fig. 2. Precise Motion Stage

TABLE I
MOTION STAGE SPECIFICATIONS

Parameter ($Unit$)	Value
Max. Acceleration (m/s^2)	5
Max. Velocity (m/s)	0.1
Peak Force (N)	12
Continuous Force (N)	3
Position Resolution (nm)	10
Single Stage Mass (kg)	0.6
Building Material	Aluminum

Trajectory generation algorithm satisfying these requirements is determined to be time based spline approximation in combination with preview controller [19, 20, 21]. Time based spline approximation is incorporating both time and geometrical position together resulting in motion that shows the smooth transitions in position, velocity and acceleration.

After the time based spline approximation is applied and corresponding polynomial coefficients are calculated, the position, velocity and acceleration commands at a given sampling time can be found using following equations [21]:

$$\begin{aligned} x_n(t_n) &= \alpha_n t_n^3 + \beta_n t_n^2 + \gamma_n t_n + \delta_n \\ \dot{x}_n(t_n) &= 3\alpha_n t_n^2 + 2\beta_n t_n + \gamma_n \\ \ddot{x}_n(t_n) &= 6\alpha_n t_n + 2\beta_n \\ n &= 1...k \end{aligned} \quad (1)$$

where k is the total number of coordinate points. α_n, β_n, γ_n are calculated polynomial coefficients and t_n is the sampling instant. The similar equations can be written for position, velocity and acceleration in y direction.

A. Model and Control of Planar Stage

For a linear positioning stage driven by the brushless direct drive linear servomotor via current controlled amplifiers, the dynamic equation of motion for each axis can be described by the following equation:

$$M_n \ddot{x} + F_l(x, \dot{x}, t) = K_{fn} i \quad (2)$$

where M_n is the nominal mass of the load experienced by the motor, K_{fn} is the motor force constant, $F_l(x, \dot{x}, t)$ represents summation of the disturbance forces, i is the current supplied to the motor x, $\dot{x}$, $\ddot{x}$ are stage position, velocity and acceleration respectively.

For the purposes of laser micromachining, the control strategy for planar stage has to be developed such that the fast motion is provided while the contouring error is minimized. There are many different ways of designing a controller for such a system. The key for laser micromachining station is the accuracy of contour tracking. Designing a contour tracking in the task space [25,26] is known technology but it suffers of the problem for having complex expressions for the control errors and complex interaction forces in the task space. Here we decided to combine a preview controller with disturbance observer as a basic control in each of the axes and the contour tracking as a correction designed on the top of the trajectory tracking preview controllers.

The core of the preview controller is actually an acceleration control with the desired acceleration, for system with compensated disturbance. Desired acceleration can be calculated using the acceleration, velocity and position references previously found using time based spline algorithm:

$$\ddot{x}_d = K_a \ddot{x}_{ref} + K_v(\dot{x}_{ref} - \dot{x}_{fb}) + K_p(x_{ref} - x_{fb}) \quad (3)$$

where K_a, K_p, K_v are positive constants, $\ddot{x}_{ref}$, $\dot{x}_{ref}$, x_{ref} are reference acceleration, velocity and position respectively, $\dot{x}_{fb}$, x_{fb} is the measured or observed velocity and measured position of the plant respectively.

Estimation of the disturbance force can be done by second order low pass filter using information of reference input current and position feedback [22]. We can write the expression for the current i supplied to the motor in the following manner:

$$i = \frac{M_n}{K_{fn}} \ddot{x}_d + \frac{g_1}{s^2 + g_2 s + g_1}(i - \frac{M_n}{K_{fn}} s^2 x_{fb}) \quad (4)$$

where g_1, g_2 are positive coefficients determining the cut-off frequency of the low pass filter.

The contour error compensating controller is designed taking into consideration the functional relationship (task formulation) for a planar motion required to follow some smooth contour with constant tangential velocity. Then the requirements of the system operation may be described by two very simple functional relations:

$$\phi(x, y) = 0 \quad (5)$$

$$v_{\phi\perp}(v_x, v_y) = v(t) \quad (6)$$

First relationship describes the contour to be tracked and the second one the requirements that velocity along the contour should be controlled to have defined time profile - usually constant. This formulation is simple but it is better to look at it from slightly different way. Taking the first equation as a constraint in the task space then it is a fact of simple geometry to formulate that velocity in constrained direction - in the direction of the gradient of the constraint contour in the current operation point - must be zero and that the tangential velocity must be equal to $v(t)$. For known reference contour $\phi(x_d, y_d) = 0$ gradient can be easily determined as:

$$[grad\{\phi_d(x_d, y_d)\}]^{\mathrm{T}} = \begin{bmatrix} \dfrac{\partial\phi(x_d, y_d)}{\partial x_d} & \dfrac{\partial\phi(x_d, y_d)}{\partial y_d} \end{bmatrix} \quad (7)$$

thus the velocity in the constrained direction is then defined as

$$v_\phi(v_x, v_y) = [grad\{\phi_d(x_d, y_d)\}]^{\mathrm{T}} \mathsf{v}_{xy} \quad (8)$$

and the tangential velocity then satisfies

$$v_{\phi\perp}(v_x, v_y) \bullet [grad\{\phi_d(x_d, y_d)\}] = 0 \quad (9)$$

where

$$v_{\phi\perp}(v_x, v_y) = [grad\{\phi_d(x_d, y_d)\}]^{\mathrm{T}}_\perp \mathsf{v}_{xy} \quad (10)$$

Now task space contour tracking can be defined by the following expressions

$$v_\phi(v_x, v_y) = [grad\{\phi_d(x_d, y_d)\}]^{\mathrm{T}} \mathsf{v}_{xy} = 0 \quad (11)$$
$$v_{\phi\perp}(v_x, v_y) = [grad\{\phi_d(x_d, y_d)\}]^{\mathrm{T}}_\perp \mathsf{v}_{xy} = v(t) \quad (12)$$

or in simpler form

$$\begin{bmatrix} v_\phi(v_x, v_y) \\ v_{\phi\perp}(v_x, v_y) \end{bmatrix} = [J] \begin{bmatrix} v_x(t) \\ v_y(t) \end{bmatrix} = \begin{bmatrix} 0 \\ v(t) \end{bmatrix} \quad (13)$$

The Jacobean matrix is defined by the gradient of the constraint contour.

$$[J] = \begin{bmatrix} [grad\{\phi_d(x_d, y_d)\}]^{\mathrm{T}} \\ [grad\{\phi_d(x_d, y_d)\}]^{\mathrm{T}}_\perp \end{bmatrix} \quad (14)$$

Now corrective control should be selected to enforce above requirements. Just taking derivative of (15) one can obtain:

$$\begin{bmatrix} a_\phi(v_x, v_y) \\ a_{\phi\perp}(v_x, v_y) \end{bmatrix} = [J] \begin{bmatrix} a_x(t) \\ a_y(t) \end{bmatrix} + \left[\dot{J}\right] \begin{bmatrix} v_x(t) \\ v_y(t) \end{bmatrix} = \begin{bmatrix} 0 \\ v(t) \end{bmatrix} \quad (15)$$

The design of the controller is fairly simple after this point. The simulation results for this controller are shown in the next section.

B. Autofocusing

Laser autofocusing mechanism plays an important role in the design of laser micromachining workstation. Although lasers used in material processing are typically high energy lasers, light beam still needs to be focused in order to achieve higher energy density and smaller final spot size. Some work has previously been done on the development of algorithm for control of autofocusing system and design of such system that could serve the purpose of autofocusing in the laser micromachining workstation. This work was presented in [23]. The core of the algorithm for the control of autofocusing system is the sliding mode optimization algorithm [24] with some adaptations to the different type of plant. It was observed that chattering problem associated with sliding mode control comes to effect and it degrades the performance of this kind of system. Further work on the improvement of performance of algorithm has been done and chattering problem has been tackled by simple linearization - a continuous approximation of SMC. Discontinuous relay and sign functions are approximated as follows:

$$\chi(\sigma) = \begin{cases} \frac{\sigma}{h}, & |\sigma| < h \\ \frac{\sigma}{|\sigma|}, & |\sigma| \geq h \end{cases} \quad (16)$$

$$v(\sigma) = \begin{cases} 1, & \sigma < -h \\ m\sigma + b, & -h \leq \sigma \leq h \\ 0, & \sigma \geq h \end{cases} \quad (17)$$

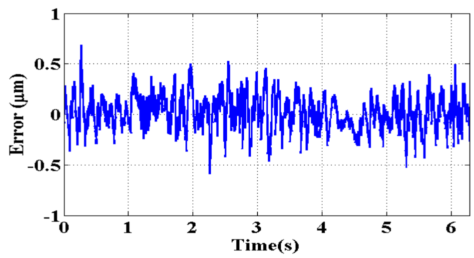
where $\chi(\sigma)$ and $v(\sigma)$ are the sign and relay functions respectively, σ is the switching surface, h is the hysteresis and m and b are the slope and offset of the approximating line. The performance of autofocusing algorithm implementation are validated experimentally and the results are given in the next section.

IV. Simulation and Experimental Results

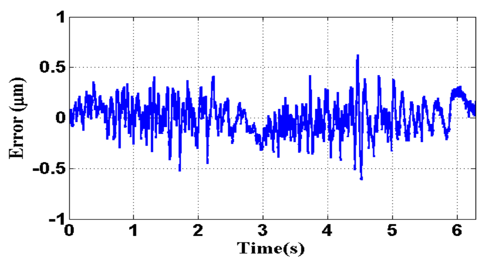
A. Motion control experiment

In order to test the performance of the controller and to justify the reliability of the trajectory generation algorithm to be used for laser micromachining purposes, an experiment that shows the motion control performance for precise positioning has been performed.

Experiment was done in the following way; technical drawing containing geometrical description of the part to be machined is supplied to software in .dxf file format. Software further parses this file and interpolates coordinate data. Time based spline approximation is applied to the interpolated data and finally the acceleration, velocity and position references are obtained and supplied to the controller. An experiment is done for the circle reference whose radius is 30 μm. The results for the trajectory tracking are shown in the Fig. 4. Tracking errors for each axis are shown in Fig. 3a and Fig. 3b. Errors are generally lower than 0.5 μm, reaching 0.8 μm at the peak points for some instances throughout the motion. The errors can be characterized to be due to the sources of noise in the system and due to the errors in the disturbance force estimation. Experimental results show good tracking performance for fairly small geometrical features. The demonstrated performance of the designed motion control system is acceptable for the use in the laser micromachining workstation since the approximated laser beam waist diameter is around 10.8 μm. The relative difference in sizes between the tracking error and laser beam waist diameter guaranty that the tracking errors will not have negative impact on the quality of laser micromachining process.



(a) Error in x direction



(b) Error in y direction

Fig. 3. Positioning Errors

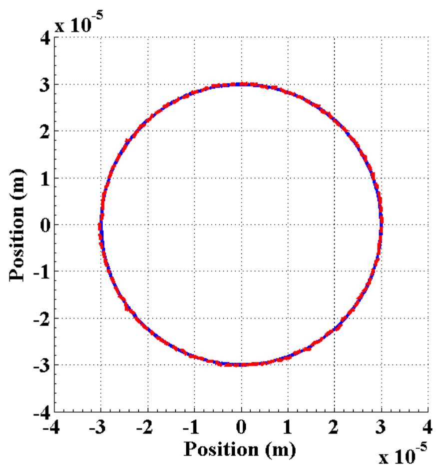


Fig. 4. Trajectory Tracking - 30μm Reference

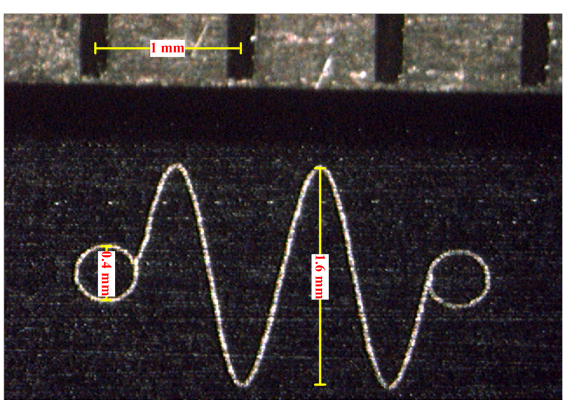


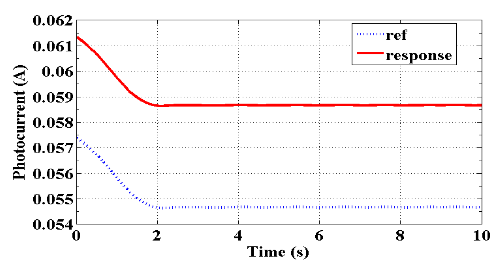
Fig. 5. Precision marking of colored aluminum

B. Precision Marking Experiment

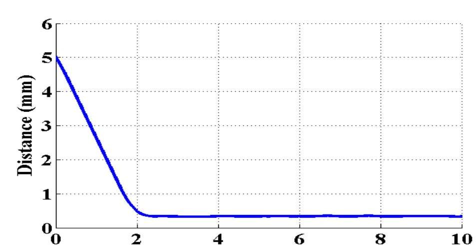
This experiment shows the precision marking of colored anodized aluminum using laser micromachining workstation. Laser is used to effectively remove the anodized aluminum giving a very high contrast and permanent mark. The experiment was performed on the black anodized aluminum alloy (6061). Laser was used in the pulsed mode and the pulse repetition rate was set to 25 KHz, the pulse width to 200 *nm* and per-pulse energy to 8mJ. The laser was run at 25 % of its total average power, namely 5W. Obtained results are shown in the Fig. 5. and the feature sizes are marked. The colored layer on the anodized aluminum is removed through thermal process. This shape is formed on the surface of aluminum by a single pass of the focused laser beam.

C. Autofocusing experiment

Experimental results for the implementation of modified autofocusing algorithm are presented in Fig. 6. The experiment was conducted on setup described in [21]. Translational stage is initially positioned away from the focal spot of the lens. System starts to move in order to minimize output, thus reaches the focal point of the lens. The results are shown in the Fig. 6a. The theoretical formulation is justified, convergence of output to the minimum point is observed. The vertical distance change between test laser and the photodiode can be understood by observing the output of the translation mechanism position encoder, shown in the Fig. 6b. Modified version the autofocusing algorithm shows performance improvements in the behavior of the system around a minimum point.



(a) Reference and Response Photocurrent values



(b) Encoder Readout

Fig. 6. Autofocusing Experiment Results

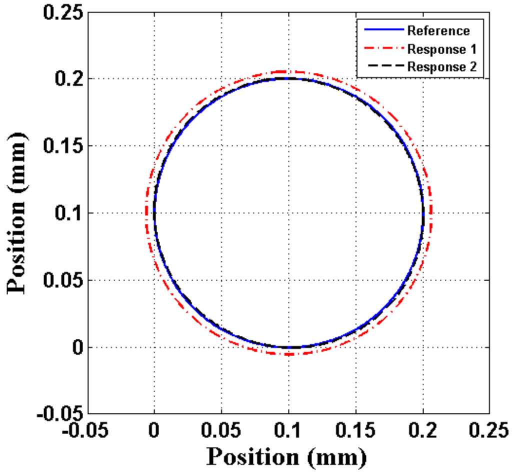


Fig. 7. Contour Controller

D. Contour Error Compensating Controller Simulation

As discussed in the previous section contour error compensating controller must be designed to guaranty precision micromachining. This controller acts as the corrective controller together with the controller described in the Eq. 4. Fig. 7. shows the simulation results for the compensation controller. It is worth of noting that this controller has almost no significant contribution to the contour tracking at low speeds. However at high speeds its effect is significant. This can be understood by looking at the Fig. 7. where contour labeled as $Response1$ is the response of the system under consideration without compensation controller and $Response2$ is the response of the system with compensation controller . The reference contour is circle with 100 μm and reference tangential velocity is 10 $\frac{mm}{s}$. The controller compensates errors successfully.

V. Conclusion

In this paper the design and realization of general purpose laser micromachining workstation is presented. The workstation could be easily adapted to the use in different environments. Efficient trajectory generation algorithm together with control strategy, for the motion platform currently featured on the workstation, is discussed and relevant experimental results are presented. Results of the given motion controller are found to be satisfactory for the purposes of laser micromachining process. The automatic focusing algorithm points out to a possibility to use PSD with simple optimization scheme to keep laser focus. Finally the precision marking of anodized aluminum experimental results are presented to demonstrate the functionality of the designed workstation. The workstation shows good performance in marking of micro- and millimetric features.

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References

[1] Masuzawa T., *State of the Art of Micromachining* CIRP, vol. 49/2, 2000, pp. 473-488.

[2] Y.Qin,A.Brockett,Y. Ma,A. Razali,J. Zhao,C. Harrison,*Micromanufacturing: research, technology outcomes and development issues* Int J Adv Manuf Technol (2010) 47:821-837

[3] J. Meijer, *Laser beam machining (LBM), state of the art and new opportunities* J. of Mat.Proc.Tech. Vol.149,Iss.1-3,2004,pp 2-17

[4] G N. Bloembergen, *Laser - material interactions, fundamentals and applications* Laser Ablation: Mechanisms and Applications II, AIP Conf. Proc. J. C. Miller, D. B. Geohegan eds., 288 (1994).

[5] J. C. Miller, *History, scope and the future of laser ablation* Ablation, Principles and Applications, Springer- Verlag (1994).

[6] Y. Kawamura, K. Toyoda and S. Namba, *Effective deep ultraviolet photoetching of polymethyl methacrylate by an excimer laser* Phys. Lett. 40, 374 (1982).

[7] R. Srinivasan and V. Mayne-Banton, *Self-developing photoetching of poly(ethylene terephthalate) films by far ultraviolet excimer laser radiation* Appl. Phys. Lett. 41, 576 (1982)

[8] F. Dabby, Un-Chul Paek, *High-intensity laser-induced vaporization and explosion of solid material* IEEE Journal of Quantum Electronics, vol.8, no.2, pp. 106- 111, (1972)

[9] M. F. Modest, H. Abakians, *Heat Conduction in a Moving Semi-Infinite Solid Subjected to Pulsed Laser Irradiation* J. Heat Transfer, no.108,pp.597-601 (1986).

[10] Richard Berenyi, *Simulating the laser micromachining of a 3D flexible structure,* Microsystems Technology 15:1855-1860 (2009)

[11] George Chryssolouris, *Laser Machining: Theory and Practice*, 1st ed. Springer Verlag, New York, NY, 1st ed., (1991).

[12] K. Kim, Y.M. Choi, D.G. Gweon, M. G. Lee, *A novel laser micro/nano-machining system for FPD process* Jour. of Materials Processing Tech., Vol. 201, 2008, pp 497-501,

[13] K. Venkatakrishnan, B. Tan, P. Stanley, L.E.N. Lim and B.K.A. Ngoi, *Femtosecond pulsed laser direct writing system* Opt. Eng. 41 6 (2002), pp. 1441-1445.

[14] H. Beckerab, R. Casparya, C. Toepfera, M. V. Schickfusa, S. Hunklinger, *Low-cost direct writing lithography system for the sub-micron range* J. of Mod. Optics, Vol. 44, Iss. 9,1997,pp 1715-23

[15] Liu, Chunyang; Fu, Xing; Wu, Yong; Li, Yi; Sun, Fengming; Hu, Xiaotang;, *Realization of nanosecond pulse laser micromachining system* Journal of Vacuum Sci. and Tech. B: Microelectronics and Nanometer Structures , vol.27, no.3, pp.1319-1322, 2009

[16] http://www.spilasers.com/

[17] http://www.haaslti.com/

[18] http://images.autodesk.com/adsk/files/acad_dxf0.pdf

[19] Inoue, T., Morimoto, M., Ohnishi, K., *A Preview Controller with Time Based Spline Approximation for Multi-axis Manipulator* IECON 2006, pp.247-251, 2006

[20] H. Kopka and P. W. Daly, *Trajectory Tracking Control of Mobile Robot by Fluid Model* Harlow, England: Addison-Wesley, 1999.

[21] J. Miyata, T. Murakami, *Trajectory tracking control of mobile robot by fluid model* Elec. and Comm. in Japan Vol. 91, Iss. 5, 2008

[22] Asif Sabanovic and Kouhei Ohnishi, *Motion Control Systems* John Wiley & Sons, Singapore, 1st ed. (2011)

[23] E.Golubovic, I.S.M. Khalil, A. Kamadan, A. Sabanovic *Laser Autofocusing: A Sliding Mode Approach* 36th Annual Conference on IEEE Industrial Electronics Society, pp.2396-2401 (2010)

[24] Utkin, V., *Sliding mode control and optimizationm* New York: Springer- Verlag (1992).

[25] Chiu, G.T., Tomizuka, M. *Contouring control of machine tool feed drive systems: a task coordinate frame approach* IEEE Trans. Control Systems Tech.,vol.9, no.1, pp.130-139, 2001

[26] Li Xu, Bin Yao. *Coordinated adaptive robust contour tracking of linear-motor-driven tables in task space* Decision and Control, 2000. Proc. of the 39th IEEE Conf. on pp.2430-2435 vol.3, 2000