DESIGN AND REALIZATION OF LASER MICROMACHINING SYSTEM

by

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DESIGN AND REALIZATION OF 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 an important micromanufacturing technique for many industrial and research applications. The popularity of this technique lies mostly in its noncontact nature. 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. For the purposes of achieving of precise and high quality laser micromachining and for full exploration of laser advantages as microprocessing tool, the development of reliable and easy to use laser micromachining system is of great importance.

In this thesis, the design approach to the general purpose laser micromachining system is discussed. Detailed description of implementation of each module of the system is given. The designed laser micromachining system can be used for many microprocessing applications such as micromarking, microchannels machining, thin film cutting, etc. The design of the precise positioning planar x-y stage and trajectory generation and control method for this stage are discussed. The development of software and man machine interface for laser micromachining system is also presented.

In order to verify the functional and operational capabilities of the designed system, precise aluminum marking, subsurface marking of glass, brass ablation and drilling of miniature holes in brass are preformed and experimental results are presented.

LAZER MİKRO İŞLEME SİSTEMİ TASARIMI VE ÜRETİMİ

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Anahtar Kelimeler: Laser Mikro İşleme, Laser Mikro İşleme Sistemi, Mekatronik Sistem Tasarımı, Hassas Hareket Kontrolu

ÖZET

Mikrosistemlerin ve minyatür aygıtların üretimi geleneksel olmayan mikro işleme tekniklerinin kullanılmasını gerektirir. Geçtiğimiz birkaç on yıllık süreçte lazerle mikro işleme birçok endüstriyel ve araştırma uygulamarında kullanılan önemli bir mikro üretim tekniği haline gelmiştir. Bu tekniğin yaygın biçimde kullanılırlığı en çok temassız gerçekleşen bir işlem oluşundan kaynaklanmaktadır. Lazerle mikro işlemenin karakteristik özelliği birçok farklı malzeme için çok küçük parçalar üzerinde ışımaya maruz kalmayan alanlara asgari hasar verecek şekilde eritme veya aşındırma işlemi yapılmasına olanak sağlamasıdır. Lazerle mikro işlemenin hassas ve yüksek kalitede yapılabilmesi ve lazerin mikro işleme aracı olarak avantajlarının tam anlamıyla araştırılabilmesi adına güvenilir ve kullanımı kolay bir lazerle mikro işleme sistemi geliştirilmesinin önemi büyüktür.

Bu tezde genel kullanıma yönelik lazerle mikro işleme sistemi tasarım yaklaşımı tartışılmıştır. Sistemin her bir modülünün nasıl meydana getirildiğine yönelik detaylı anlatımlar mevcuttur. Tasarlanan lazerle mikro işleme sistemi mikro işaretleme, mikro kanal açma, ince film kesimi gibi bir çok farklı uygulama amacıyla kullanılabilir. Hassas konumlandırma amaçlı düzlemsel x-y platformunun tasarımından ve bu platform için gezinge yaratımı ve kontrol metodundan bahsedilmiştir. Lazerle mikro işleme sistemi için yazılım ve insan makine arayüzü geliştirilmesi de sunulmuştur.

Tasarlanan sistemin fonksiyonel ve operasyonel yetkinliklerini doğrulamak adına hassas aluminyum işaretleme, cam için yüzey altı işaretleme, pirinç alaşım eritme ve minyatür delikler açma işlemleri gerçekleştirilmiş ve deneysel sonuçlar sunulmuştur.

“To my mom and aunt”

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1 INTRODUCTION

1.1 Motivation

In the past few decades, the development of miniature devices containing multifunctional and complex geometry parts in micro/nano scale is driven by the social and economical necessity to increase the quality of life. Nanotechnology field requires new, innovative, ever effective – revolutionary manufacturing processes and tools to be utilized. Enabling technology for nanotechnology is commonly believed to be, among others, development of functional microelectromechanical systems (MEMS), i.e. tools for controlling of matter in nanoscale should be developed in the micro and mezo scale. Although the miniaturization trend is most profoundly demonstrated by the semiconductor industry and the manufacturing of integrated circuits, it also plays an important role in automotive, medical, military, aerospace and telecommunication industries [1]. In each of these industries there is a growing need to develop components and systems with ever smaller dimensions while maintaining functionality and increasing efficiency.

The advancements in the industrial miniaturization are owed to the microfabrication techniques developed by the end of the 20th century to satisfy the production needs of microelectronics industry. Many of these fabrication techniques are adapted to MEMS fabrication. Although these microfabrication techniques offer many advantages, they still have limitations that are needed to be overcome in order to allow further technological progress in miniaturization. These limitations are most evident in terms of material types (limited mostly to silicon and thin metallic coatings), component geometry (mostly planar, two dimensions), performance requirements (parts flexibility and strength) and cost (serial, single custom parts, production is economically inefficient). Due to these limitations alternative fabrication techniques were developed in order to enable production of 3D structural components and devices made of a wide range of materials with required functionality, flexibility and strength. Some of the most popular alternative microfabrication techniques are; Micro-EDM, Laser Micromachining, Ultrasonic Micromachining, Mechanical Micromachining, Micromolding/Microcasting, Micropunching, etc [1].

Among the abovementioned microfabrication techniques, laser micromachining is a technique that has gained a lot of popularity primarily due to the advances in laser industry and due to the many unique advantages and distinct capabilities. Lasers are unique energy sources identified by the very narrow wavelength-energy window, excellent spatial and temporal coherence and relatively high average and peak light intensity. Due to these features, lasers found their place in material removal applications. Although initially used for macro scale applications such as cutting, drilling and welding, lasers also found their place in micromachining applications as soon as the tunability of the wavelength and pulse length, hence very precise and controllable material removal, was possible. Despite the fact that laser micromachining is a serial process that results in slower fabrication speeds for large parts, it is ideally suited for small scale production, prototyping, and customization. On small scales, lasers are capable of manufacturing throughput rates greater than those achievable by mechanical means such as milling or drilling.

There is a number of microprocessing applications where lasers became dominant tools. For example, producing microvia holes in high-density interconnect circuits, manufacturing of filter Bragg gratings, prototyping of microfluidic devices, integration of numerous microsystems are being performed with the help of lasers, and production of stents and gas and liquid flow control orifices for advanced drug-delivery catheters and aspirators.

For the purpose of achieving of precise and high quality laser micromachining and for full exploration of laser advantages as microprocessing tool, it is necessary to develop modular, easy to use and reliable laser micromachining system. Considering testing of laser micromachining process models, testing of newly developed ultrashort pulsed lasers technology and performing research in materials science with focus on laser-material interaction, development of laser micromachining systems is of great importance.

1.2 Objectives

The main objective in this thesis is the design and realization of a modular, easy to use and reliable laser micromachining system for precise and high quality laser micromachining operations.

Motion control of laser micromachining systems provides motion between the focused laser beam and the micromachining sample in order to impose a desired pattern and correct orientation of the desired pattern on the workpiece. Normally, laser micromachined feature sizes range from few microns (lower limit resolution is limited to the laser spot size) up to hundreds of microns.

The emphasis of this thesis is on the design of motion control systems, the design and development of precise positioning linear planar stage having resolution, accuracy and repeatability of submicron range.

The success of laser micromachining is mandated by the proper adjustment of process parameters. Process models are available in literature for some laser micromachining processes, however, critical process parameters are mostly adjusted by performing series of experiments. These experiments are usually done by whether altering laser or material parameters, recording results then selecting of optimum set of parameters.

Another emphasis of this thesis is on the design of laser micromachining system software together with man machine interface that will allow both manual and automatic alteration of critical process parameters such as laser power, pulse repetition rate, pulse duration, etc.

Laser micromachining system integration typically involves laser equipment with beam delivery optics, motion control device responsible for providing of relative motion between the workpiece and laser beam, control hardware and computer with software and man machine interface responsible for process, laser and overall system parameters adjustment and control. Second objective of this thesis is to design mechanical structure that will provide enclosure for all the modules of system in an efficient way, while minimizing the sources of process errors arising due to the improper geometrical alignment and machine vibrations.

1.3 Thesis Outline

In the second chapter general information about laser micromachining, the state of art in laser micromachining technology and the information about existing laser micromachining systems are presented. The state of art in laser micromachining is organized by application industry specific developments.

The main design requirements for laser micromachining system are discussed in detail in Chapter 3. Design requirements for mechanical structure, motion control system including positioning mechanism, control and autofocusing, laser system, beam delivery optics and software together with man machine interface are proposed.

Chapter 4 shows the technical details of the implementation of the overall laser micromachining system. The implementation of mechanical structure, the design of planar x-y motion stage together with the motion planning algorithm development and control of stages, implementation of autofocusing system, discussion on overall system controller, laser system and beam delivery optics selection and software and MMI development are discussed in details.

In order to verify the operational and functional capabilities of the designed laser micromachining system series of motion control and laser micromachining experiments were preformed. The experimental results and the evaluation of these results are given in Chapter 5.

Chapter 6 includes the conclusions of this thesis and points out the achievements and future research motivation.

2 STATE OF ART IN LASER MICROMACHINING

2.1 General Information about Laser Micromachining

The use of conventional micromachining methods is usually restricted due to the challenging design requirements, use of materials with advanced properties, complex shape and unusual size of parts to be fabricated. As a result of this fact the miniaturization trend in product development requires the advancement of nonconventional micromachining methods. In order to find a suitable nonconventional manufacturing method for a given application a comparative analysis should be made to guaranty correct selection and successful outcome of the specific process. A lot of information about nonconventional manufacturing methods can be found in literature; therefore detailed description of these methods is not offered in this work.

Laser micromachining is a distinctive microprocessing method that has gained a lot of interest in research and industry mostly due to its applicability to almost whole range of engineering materials, high quality surface finish and growing research interest in the area of laser technology. Laser systems are being employed increasingly in many diverse industry sectors such as automotive, telecommunications, biomedicine, military, display devices, printing technologies and semiconductors. Most important advantages this technique offers over other microfabrication techniques are:

- Non-contact processing. Laser beam loose almost no energy on its way toward workpiece and it doesn’t have physical contact with the workpiece during the microprocessing. Processing can be done in any medium including vacum, air or even liquid.
- High resolution processing due to the small spot size. Laser beams have excellent focus ability due to the high quality beams, monochromacity and high quality of the optical equipment used. Lasers currently used for micromachining purposes can be focused down to spot sizes of few micrometers.

- Good and consistent quality. Laser processing offers low heat input, little distortion and small heat affected zone. This advantage is mostly owed to pulsed lasers with very short pulse durations.
- Processed material doesn't require any post- or pre-processing. This particular advantage can be time and money saving.
- High power/energy densities. This advantage contributes to the increased speed of the processes and ability to machine difficult to machine (DTM) materials
- Easy process automation.
- Economical. The prices of industrial laser systems are decreasing and they have become very affordable in the last decade.

The above listed advantages are related both to the laser micromachining process and equipment used. Minimum obtainable spot size and the quality of the processed micro features are related to the wavelength of the laser, laser beam quality, stability and polarization state of the laser beam, as well as the quality of the optics used. Generally pulsed lasers that can deliver ultrashort pulses (in the order of femtoseconds) with high pulse energy and high repetition rates that are desired in the high resolution laser micromachining process. When considering the quality of the laser micromachining process, laser unit is not the only important factor to be taken into account. Overall configuration and design of the system for the process utilization plays another crucial role. Mechanical structure of the system, measurement equipment, control methods employed and overall system integration have significant effect on the laser micromachining process quality.

Material removal in laser micromachining can be done using two methods. One uses a power source that emits a beam with very high quantum energy. If the energy exceeds the binding energy among atoms of the workpiece each molecule can be decomposed directly into atoms and removed from the workpiece. The other method uses an energy beam of which incident power density on the workpiece is extremely high such that high power enables the removal of the material from workpiece by vaporization, skipping the phase of melting.

The system dedicated for the laser micromachining can be designed in many different ways as long as its configuration satisfies the requirements of the technique being used to perform laser micromachining. There are two techniques currently used in laser micromachining technology, a mask projection technique and laser direct write technique.

In mask projection laser beam doesn't directly write on the sample. The mask is projected onto a workpiece using a high resolution lens. Mask projection method is particularly suited to excimer lasers since their optical properties mean that direct beam focusing is not usually an attractive option. Mask projection methods used with excimer lasers can provide many desirable features such as high feature resolution, fine depth control, excellent reproducibility and the ability to cover large sample areas. In standard mask projection systems, the depth of the micro-structures is controlled by the numbers of laser shots which are fired and the resolution of the features are determined by the mask and the optical projection system. Advantage of the mask projection technique lays in the fact that the mask and workpiece can move independently which provides the flexibility in the type of the micromachined features. Disadvantage of this technique is that mask production itself can be time consuming and expensive.

In direct write systems, the laser beam is focused to a small spot using a lens and either the beam or the sample (or both) are moved relative to each other to produce the desired motion pattern while the laser shots are fired and processing is done. Direct write method is usually used with solid state or carbon dioxide lasers. Both mask projection and direct write technique are conceptual depicted in Figure 2.1. [3]

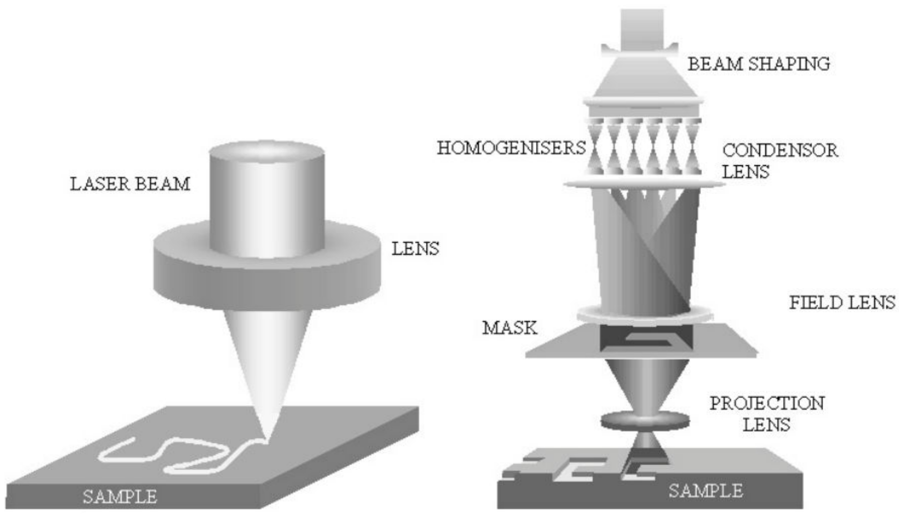


Figure 2.1. - Direct writing (left) and mask projection techniques (right) [3]

2.2 Applications of Laser Micromachining

This literature review tends to summarize some of the ongoing research in several application areas with an emphasis on the importance of laser micromachining process and system in these areas. This review is not complete, but summarizes works in order to point out the importance of laser micromachining as a fabrication technique. More extensive reviews on laser micromachining can be found in [11] and [12].

2.2.1 Aerospace Industry Applications

Miniaturization and microsystems technology has a great impact on aerospace industry because of reduction of size, mass and consequently power consumption of sensors and actuators used in spacecrafts, satellites and launch vehicles. Laser micromachining has found application in production of miniature components and microsystems for space systems with an aim to improve performance and increase the reliability of microfabricated components and systems [4].

Propulsion is vital in aerospace applications. Miniaturization of propulsion system has led to the development of microthrusters. Microthrusters are used for propulsion and attitude control in small space satellites. Microthrusters can also be used for dynamic suppression/damping of vibrations in extended space structures. In [5] authors successfully applied laser direct-write processing technique for rapid prototyping and development of various fluidic components and a microthruster subsystem in a photostructurable glass/ceramic material.

In [6] three fabrication methods, namely reactive ion etching, femtosecond laser machining (FLM) and a combination of powderblasting and heat treatment, have been investigated to make a conical converging-diverging nozzle for microthruster application. Laser micromachining technique, with further improvements in process quality, is very promising fabrication technique for this application.

Laser micromachining of a range of aerospace materials with special attention to lightweight composites has been investigated in the study of [7]. The paper compares the micromachining results from novel picosecond high repetition rate fiber laser system and a femtosecond laser source.

In the study of [8] aluminum-alloy samples of slot antenna array were fabricated directly on a Nd: YAG laser cutting system and the combined effects of power and feed rate on slot size, surface roughness and striation frequency have been studied. It has been reported that the dimension size could be controlled within the error allowance in micrometer level, and the productivity is improved more effectively than that of other methods.

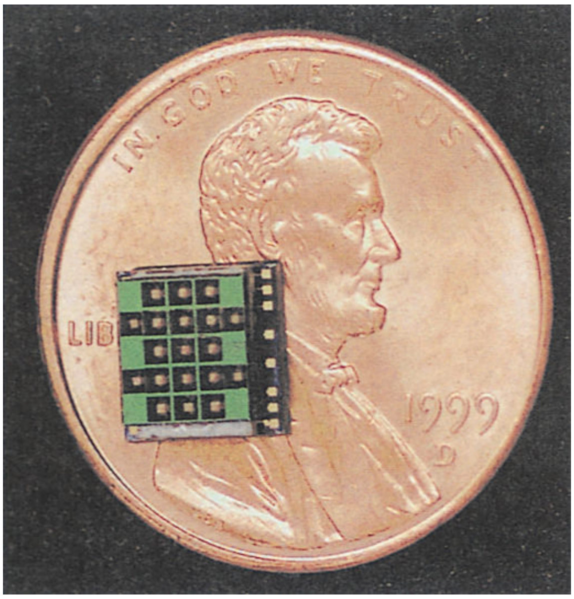


Figure 2.2. - A (3x 5) array of digitally addressable microthrusters. [9]

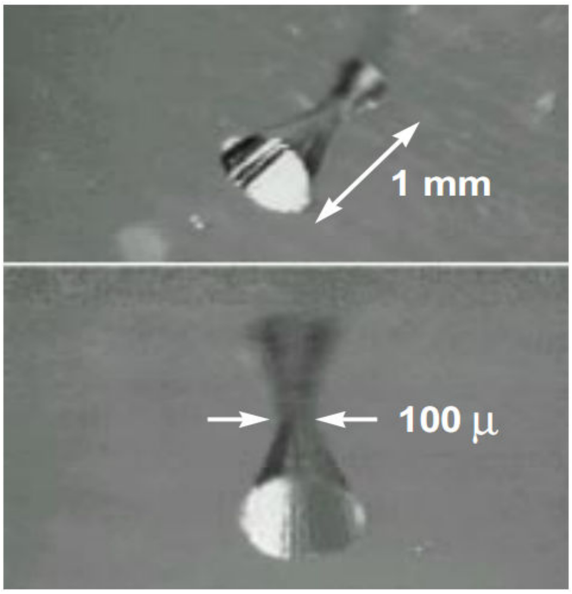


Figure 2.3. - Optical microphotographs of a laser machined converging/diverging nozzle.[10]

2.2.2 Automotive Industry Applications

Laser systems are not new to automobile industry; they have been used for cutting and welding of macroscopic parts of automobiles for many years. Recently laser systems started to be employed for production of fine, microscopic parts of automobile components.

Some of the issues modern automotive industry is concerned about are increasing of security, improvement of combustion efficiency and reduction of hazardous emission to environment. In [13] authors report employment of laser system in order to manufacture high quality holes, diameters less than 145 μm, for fuel injection nozzles. Laser micromachining technique was combined with EDM technique achieve minimum total drilling time and the best quality holes.

Laser micromachining has found its place in manufacturing of sensors used in automotive industry. MEMS sensors are highly desirable for measuring engine exhaust streams in corrosive, high temperature environments or monitoring extreme pressures. One such example can be found in the study of [14], femtosecond-pulsed laser micromachining of 250 μm thick 4H–SiC single crystal wafers for production of pressure sensor was successfully performed with the benefits of high etch rates and drilling speeds. Excellent control of thickness, high aspect ratio, high spatial resolution and thin diaphragms were achieved through non-thermal ablation mechanisms.

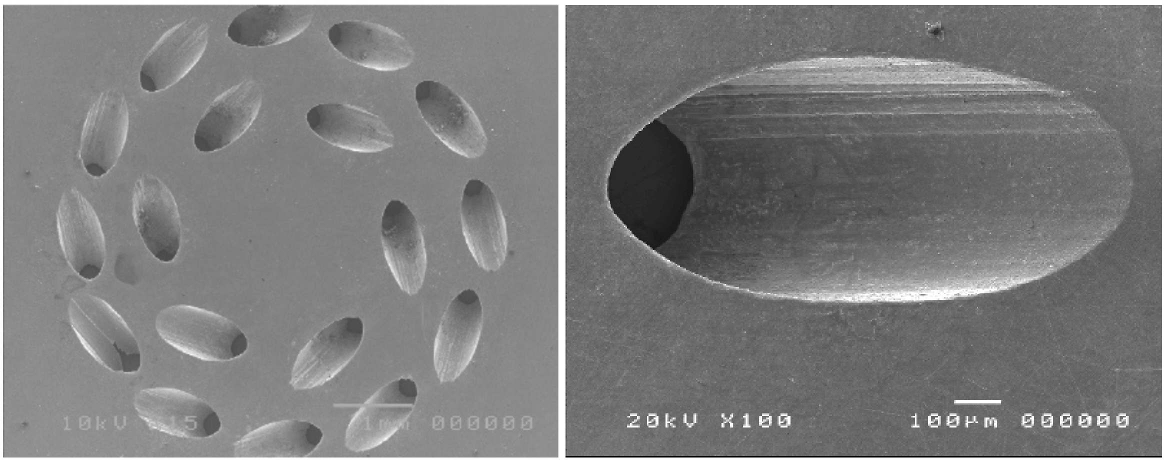


Figure 2.4. - Gasoline injector for a high performance racing engine (left) and high magnification of one of the holes (right) [31]

2.2.3 Biomedical Industry Applications

There have been many advances in the development of microstructured biomedical devices for use in minimally invasive surgery and other advanced surgical techniques. The complexity and small feature sizes required in these devices necessitates the use of laser micromachining and other advanced micromachining techniques. For example, coronary stents are medical devices that are implanted within the coronary arteries in order to maintain the flow of blood to the muscle tissues in the walls of the heart. These devices are used in conjunction with balloon catheters in order to treat lesions (blockages) in the coronary arteries. The cutting process of a slotted tube coronary stent is presented in [15].

In [16] it is shown that laser bonding achieves hermetic sealing and good bond strength with minimum heat input into the part, making it a technique of choice for the encapsulation of biomedical implantable devices such as pacemakers. This paper describes some of the latest achievements in laser micro-joining of dissimilar and biocompatible materials for microsystems and biomedical devices.

In [17] laser direct writing and percussion-drilling techniques are employed to fabricate two biodegradable micro-devices for biomedical engineering applications. Biodegradable polymeric material, poly-D-lactic acid (PDLA), and polymer poly-vinyl alcohol (PVA) were micropatterned by ultraviolet lasers. The experimental results for producing micro-devices are reported. This work on laser micromachining of a biodegradable polymer for applications in biomedical engineering is the first of its kind and demonstrated that this technique is well suited to produce biodegradable microdevices with minimum thermal damage to the surrounding material.

In order for pulsed laser micromachining to be widely accepted in the biomedical devices production industry it requires intense research on process optimization. One such work is presented in [18].

Ti-6Al-4V is an alpha-beta titanium alloy that is extensively used in hip prostheses, knee prostheses, dental implants, and other medical devices. Surface roughening, porous coatings, and bioactive ceramic (e.g., hydroxyapatite) coatings are commonly used to enable the growth of bone-forming cells (osteoblasts) on the surface of Ti-6Al-4V implants. These modified surfaces are used to promote implant fixation by means of bony tissue growth around an implant, which is referred to as osseointegration. Conventional surface modification techniques may result in alteration of implant surface chemistry or formation of debris that could participate in implant wear. Fasai et al. used laser micromachining to produce microscale grooves for cell growth and alignment on Ti-6Al-4V surfaces. [19]

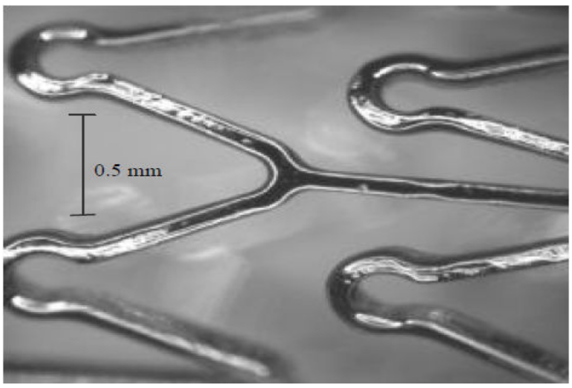


Figure 2.5. - Laser cut stainless steel stent [20]

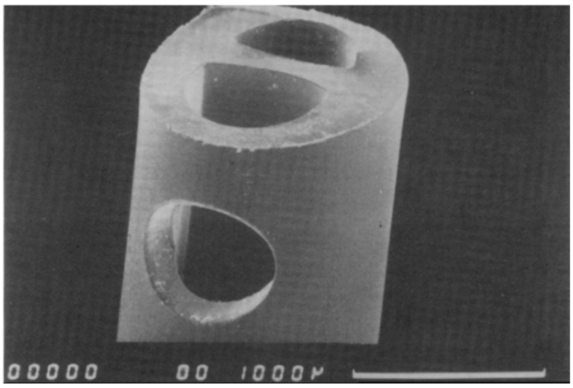


Figure 2.6. – 0.7 mm diameter hole for blood passage drilled with a laser [21]

2.2.4 Biotechnology and Microfluidics Industry Applications

Microfluidics is an emerging technology that involves manipulation of small volumes of fluids. Microfluidic devices have numerous medical applications, including use in clinical pathology (e.g. DNA microarrays) and clinical medicine (e.g., drug delivery devices). Many microfluidic devices contain a network of microscale channels that enable very small volumes of fluids to be assayed or transported. Laser micromachining is the preferred method for rapid prototyping of microfluidic devices since the design of a given device may be rapidly altered through modification of the CAD data file that is used to guide the laser and/or the substrate.

Significant efforts are underway to fabricate microfluidic devices on polymeric substrates; it is anticipated that polymeric microfluidic devices could be fabricated at low cost using laser micromachining [22]. In [23] the use of laser micromachining to fabricate polymeric microfluidic devices has been reviewed.

Femtosecond laser micromachining may be used to fabricate three-dimensional microfluidic devices. Fabrication of embedded, three-dimensional microfluidic channels has been achieved by exposure of photosensitive glass to femtosecond laser energy followed by etching with hydrofluoric acid [24].

Another recent trend in microfluidics involves integrating optical, electrical, or chemical sensing elements with microfluidic channels. Laser micromachining has been used to fabricate these integrated microfluidic devices. In [25] authors demonstrate the fabrication of integrated microfluidic channels, which contain optical waveguides on a fused silica substrate.

[26] presents a new method for rapid fabrication of polymeric micromold masters for the manufacture of polymer microfluidic devices. The manufacturing method involves laser micromachining of the desired structure of microfluidic channels in a thin metallic sheet and then hot embossing the channel structure onto PMMA substrate to form the mold master. The channeled layer of the microfluidic device is then produced by pouring the polydimethylsiloxane (PDMS) elastomer over the mold and curing it.

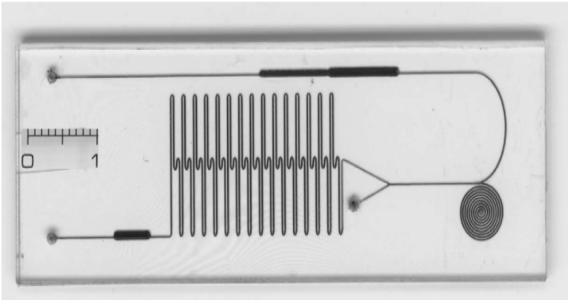


Figure 2.7. - Sample pattern fabricated in PMMA substrate. The scale bar is 1 cm. [27]

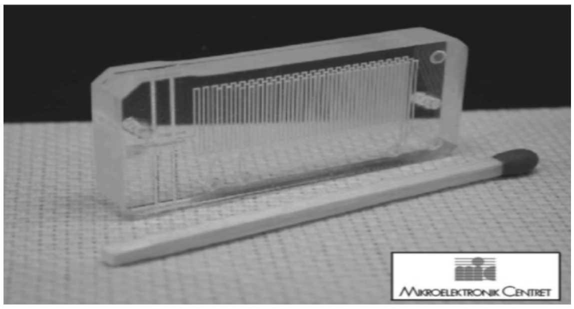


Figure 2.8. - Three-layered PMMA-microfluidic system for the detection of ammonia in aqueous samples. [22]

2.2.5 Microelectronics Industry Applications

The microelectronics industry is moving toward smaller feature sizes. The main driving forces are to improve performance and to lower cost. From the performance point of view the small distances between chips together with the short interconnection routes have of great importance in order to achieve faster operation. Laser processing applied for via generation, direct pattern processing, image transfer, contour cutting and trimming has proved to be efficient method in microelectronics industry.

Authors in [28] review of some of the emerging applications in the microelectronics industry that are well served by laser micromachining and discuss the advancements in lasers, optics and beam steering that enable cost-effective laser micromachining. It also discusses some open issues that are the subject of current and future research. Particular applications of laser micromachining such as low-K dielectric scribing, thin silicon dicing, compound semiconductor scribing and dicing and thick silicon slotting and via drilling are discussed in detail.

The drive for increased circuit density in printed circuit board (PCB) technology has led to the introduction of ultra-small internal vias (commonly referred to as microvias) in new designs of epoxy-glass multilayers boards. The use of microvias simplifies the design of complex boards. In [29] authors report the results of an investigation exploring the feasibility of laser drilled microvias. Single pulses from a CO2 were used to drill small holes in panels of epoxy glass. Both buried and blind vias were generated.

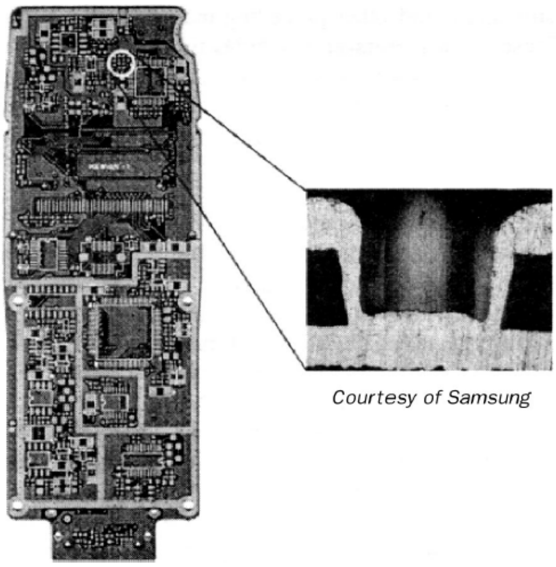


Figure 2.9. - Personal communication system with microvias. [30]

8.2.6 Nanotechnology Applications

Nanotechnology refers to the variety of techniques that are utilized in the creation of features and/or structures with minimum feature dimensions smaller than 100 nm. There are several technologies for fabriation of parts with nanosize components and features. Among the others, lasers have been successfully used for this task and this is area of research that is rapidly growing. Mostly features that are created using lasers are nanoholes, nanobumps, nanotubes and gratings.

The fundamental problem when using laser for nanotechnology applications is the resolution of processing, because resolution is determined by the diffraction limit of laser which is about half of its wavelength. However researchers use some additional techniques in combination with laser to overcome this problem. In [33] pulsed lasers were applied to combine with atomic force microscope (AFM) and nanoparticle self - assembled mask to achieve sub-30 nm patterning on the metallic surfaces. The mechanisms of the formation of nanostructure patterns are discussed in this paper.

Detailed investigations of the possibilities for using femtosecond lasers for the nanostructuring of metal layers and transparent materials are reported in [34]. Sub-wavelength microstructuring of metals is performed and the minimum structure size that can be fabricated in transparent materials is identified. Two-photon polymerization of hybrid polymers is demonstrated as a promising femtosecond laser-based nanofabrication technology.

[35] reports on nanostructure fabrication on silicon (Si) substrate by 800 nm femtosecond laser pulses. The formation of 100nm diameter nanoholes was observed using spherical alumina particles placed on the substrate surface and exposing them to femtosecond laser irradiation The dependence of nanohole formation on the laser fluence and laser pulse number was as well investigated. The mechanism for the nanohole drilling is the near-field optical enhancement effect induced by interaction between local surface plasmon on the particles surface and surface plasmon polariton on the Si substrate surface.

In order to correlate femtosecond laser beams in wide region and achieve laser ablation, beam correlators based on coherent optical system were developed in [36]. By processing thin films using this system, uniformly spaced and nano-sized structures were generated.

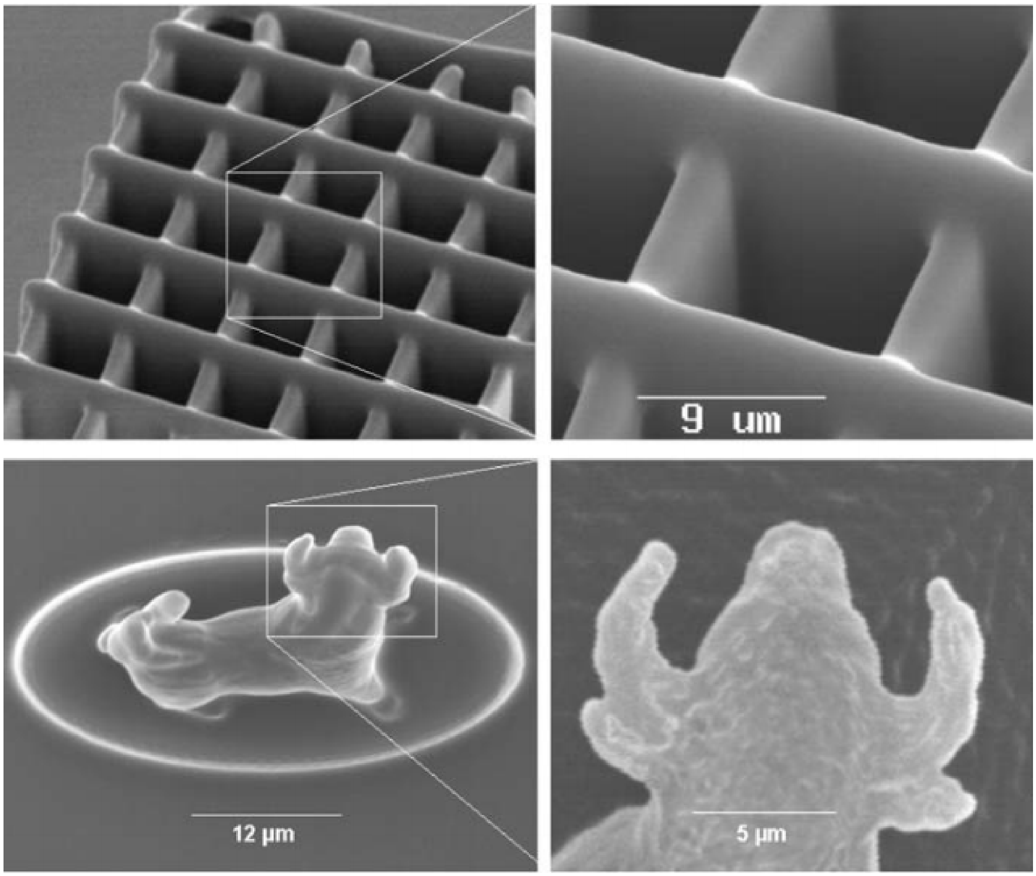


Figure 2.10. SEM images of a three-dimensional periodic structure (top) and a micro-bull statue (bottom) fabricated by two photon-polymerization in a hybrid polymer using femtosecond laser pulses. Corresponding enlarged fragments are shown on the right side of the figure [34]

2.3 Examples of Laser Micromachining Systems in Literature

Although many works were published in the field of laser micromachining, they mostly contain the research results in the laser-material interaction, exploring the ultrafast lasers machining abilities and the micromachining process optimization, not many papers are published containing the technical details about the design of laser micromachining systems. In the following few paragraphs the literature review about those existing research papers is presented.

In [43] authors present the laser micromachining system for flat panel display repair. This paper presents and introduces the design and control for an ultra-precision dual-stage system for laser machining equipments applied to FPD process. The dual-stage is decoupled type which has no mechanical coupling between the coarse and fine stages. Minimization of reaction force between the fine and coarse stages is achieved by no mechanical connections between the stages. Important approach to the modularity of the motion stage is discussed as well. Authors dedicate very little attention to the description of the system design requirements and overall configuration.

In [44] laser micromachining system that can be used for applications in the electronic and microfabrication industry is presented. An acousto-optic deflector-based scanning system has been developed for steering the femtosecond laser beam with high positional accuracy, resolution, and scan speed. The capability of the system to machine complex features with submicron line widths has been proved. Although this paper gives a lot of details on the operation of acusto-optic deflectors it doesn't contain details about the overall system integration and modules of the system.

Many technical issues and details concerning the design of the direct writing laser lithography system are discussed in [45], with the focus on the description of consisting hardware and software. Authors present a low-cost direct writing laser lithography system featuring fixed optical beam. The exposure pattern is generated by scanning of the substrate on an X-Y motion stage. The system is realized for mask design using CAD program. This paper also introduces a section on the cost calculation of laser direct writing lithography system.

In [46, 47] authors present main features and potential applications of an integrative nanosecond pulse laser micro-machining numerical control system. According to the special need for micromachining, authors designed NC system based on PCI bus and FPGA technologies. This system consists of a 3-D motion platform including a displacement signal feedback system with accuracy of 1 um, a CCD (Charge Coupled Device) monitor and a workstation. After briefly describing the laser machining system, some micro structures fabrication with different laser parameters was presented. The schematic describing this system is shown in the Figure 2.11.

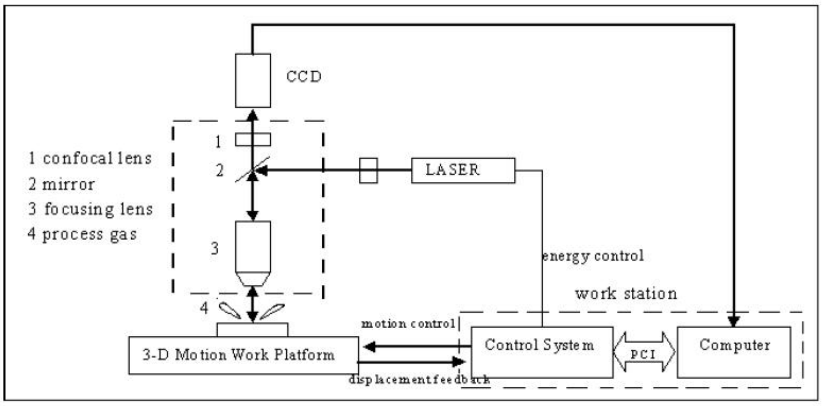


Figure 2.11. – Schematic of laser system [47]

Nd:YAG laser micromachining workstation that allows cutting on a scale of a few microns has been developed and operated in [48]. The system incorporates a telescope viewing system that allows control during the work and a software interface to translate AutoCad files. Some examples of the performance are given. Authors demonstrate the possibility of precise machining. This paper moderately contains details on the design of the workstation.

A laser micromachining workstation utilizing two industrial laser systems, a Ti:Sapphire laser capable of producing pulses of less than 150 femtoseconds and a frequency tripled Nd:YLF laser (351 nm, - 50 nsec pulsewidth) has been described in [49]. This paper describes the details about the optical design of the workstation and some micromachining results.

3 SYSTEM DESIGN REQUIREMENTS

3.1 Introduction

This chapter introduces the details on system design requirements for the design of fully functional laser micromachining system. First a general introduction into the design requirements of laser micromachining system is given, and then the design requirements for the each module of the system are discussed in details. Throughout the design process of laser micromachining system two types of design requirements were introduced; dynamic – these requirements were changing and most of them were renounced or refined after the development of first prototype and static – requirements such as the functional requirement of the overall system and desirable features, these requirements stayed relatively unchanged throughout the design process. This chapter focuses on the discussion of the static design requirements.

A laser micromachining system is generally comprised of mechanical support structure, laser system, beam delivery system, motion system, control system and software with man machine interface. Laser micromachining systems come in many different configurations for many different applications. Structurally and functionally these systems resemble the traditional laser machining systems for machining of macroscopic components; however there are many special requirements that need to be considered when designing laser micromachining system due to the microscopic nature of the laser micromachining process.

Commonly, the set of the system design requirements for the design of new machine is developed to best satisfy the needs of the customer who expects to profit from an investment into new machine. However, since the design of system described in this thesis is a result of research project and the set of requirements are not coming from a customer directly, the design specifications are rather developed from general knowledge of their value to the potential customers.

The functional requirements of the developed laser micromachining system are listed below. These requirements are used as the guidance for the development of first prototype and consequently for the final design of machine. Based on the detailed research on the laser micromachining systems, we strongly believe that these functional requirements best represent the potential customer / user needs.

- The machine must provide means of removing material from a workpiece using laser micromachining process.
- The machine should have configuration in which the relative motion between the workpiece and laser beam is utilized such that laser beam is stationary and workpiece is moving to produce desired feature in the material.
- The most general configuration requires the three-degrees-of-freedom relationship between the laser beam and the workpiece to be fully programmable under computer and/or control system hardware control.
- The working tool, laser beam, must have an access to the entire workpiece in sufficiently accurate and rigid manner i.e. the total travel distance of the motion system should be large enough for the desired application, with motion resolution in nanometer range.
- The workpiece fixture plate surface must be orthogonal with respect to the laser beam central axis i.e. no unintentional misalignment should exist between the workpiece fixture plate and laser beam.
- The machine must be configurable to interface with automatic workpiece loading system so it can be used as the part of industrial production facility of some kind.
- Software and man machine interface (MMI) should provide easy and user-friendly way of interaction with the laser micromachining system. This interaction should consist of laser parameter setting, technical drawing input, monitoring of the process and emergency stop actions.
- The machine should be designed for easy transport, operation on standard utility and footprint shouldn't exceed the typical tabletop machine footprint for easy utilization in labs.
- The work chamber must be enclosed meeting the laser safety conditions.

These functional requirements are used in the design process to determine characteristics or parameters of the design that needs to give the desired performance. The design process is hierarchical and iterative in nature. Firstly higher levels of design solution have to be determined according to which the set of new functional requirements are determined to be applied to lower levels of design. If design contains any inadequacies, often it is necessary to redesign all or the part of the system. If the economical constraints allow it is recommended to first develop physical prototype, run tests and then do the final design, otherwise first prototype can be purely conceptual.

3.2 Overall System

Figure 3.1 shows conceptual relationship among the modules of laser micromachining system. The relationship between the modules can be roughly described in the following way; laser system generates the beam with the required energy, pulse repetition frequency and pulse width which is then synchronized with the positioning system's motion; the entire system is governed by a control system which is interfaced with personal computer; beam delivery optical system (optics head) is considered as an intermediate stage between laser system and positioning system with the main aim of "bending" of the laser beam to the desired directions and increasing of the beam's energy density by focusing the beam to a tiny spot. Figure 3.1 shows only one of the possible arrangements of the optical components inside optics head. The vision system, often consisting of single camera (CCD), is generally used to monitor process. However, vision based feedback can be found in some industrial laser micromachining system serving the purpose of initial part positioning and orientation, nevertheless vision feedback is not essential for proper working of the whole system. User monitors the micromachining process and adjusts the necessary system parameters via man machine interface on the personal computer.

Integration of complex and demanding subsystems needed for proper operation of a laser micromachining system requires the design of mechanical structure that contains the other subsystems: such as the laser system, beam delivery optics, system controller and computer with some mean of graphical user interface and further allow them to function properly. An overall design of laser micromachining system follows procedures of mechatronics systems design (Figure 3.2) in which design of mechanical containment and motion control components plays a specific and important role.

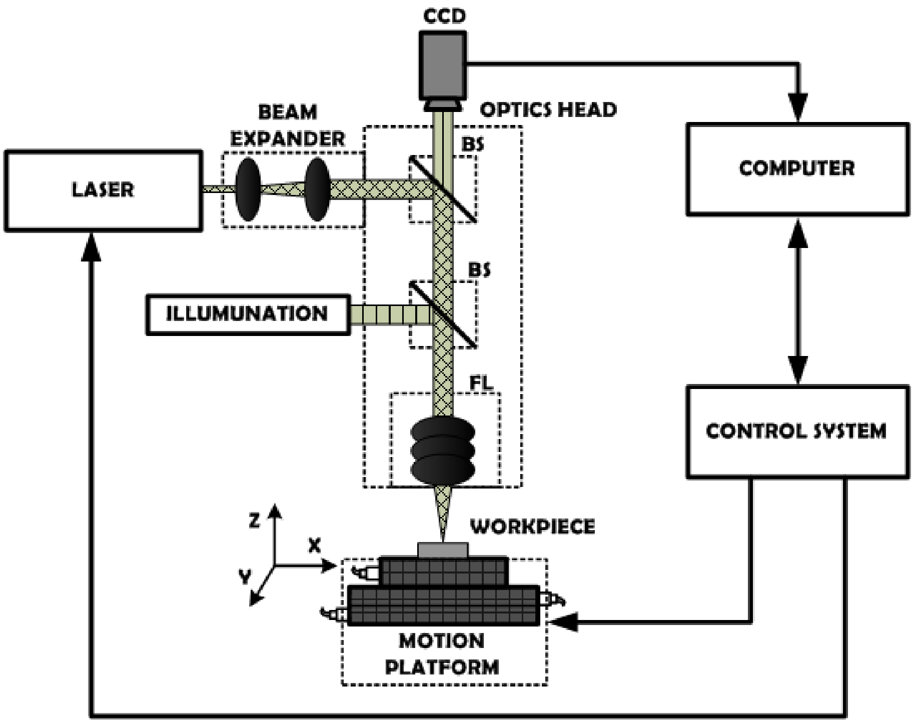


Figure 3.1. - Schematic of laser micromachining system

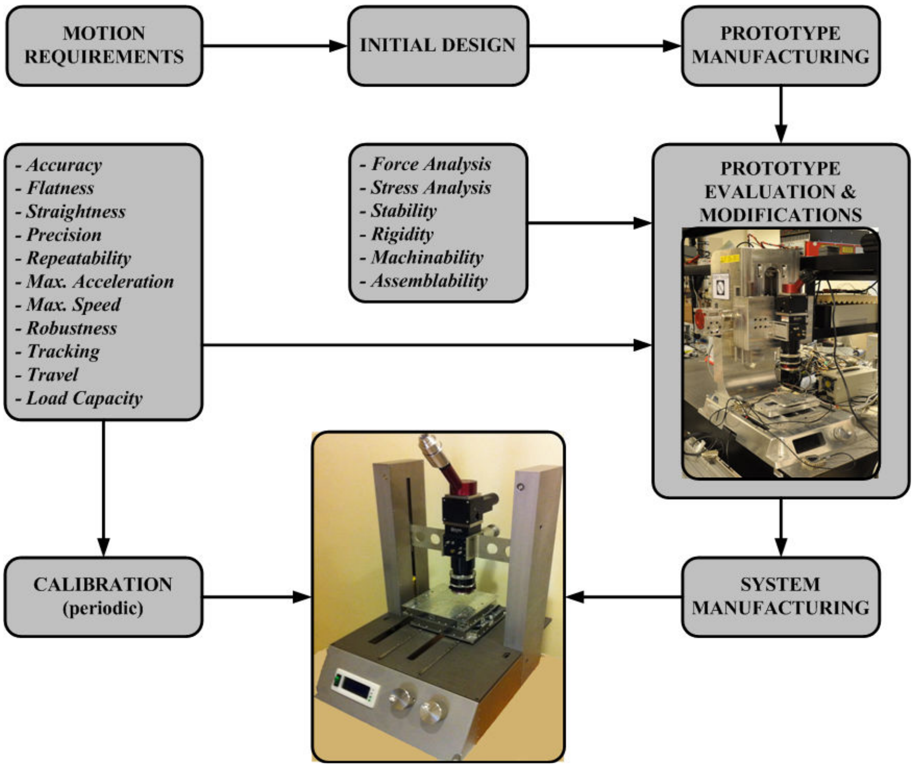


Figure 3.2. – Overall design process

3.3 Mechanical Structure

Mechanical structure of a typical laser micromachining system consists of stationary and moving mechanical modules. The stationary modules include the machine base, the column, laser housing, beam delivery optics housing and workpiece fixtures while moving modules include workpiece positioning mechanism and optics positioning mechanism.

The mechanical structural design is crucial since the structure of a machine provides the mechanical support for all of the machine's components. In order to identify the design requirements for the mechanical structure of laser micromachining system, the desired geometrical and functional relationship between the modules of the system should be studied. Independent of the laser micromachining application, this relationship can be in general defined as following; Positioning mechanism resides on the machine base; Parts to be laser micromachined, placed on a suitable part fixture, are mounted on top of the positioning mechanism; Beam delivery optics are positioned above the workpiece at a desired distance depending on the focusing lens properties; Laser system output (or fiber cord output in the case of fiber lasers) is positioned near the beam delivery optics. The computer and control hardware are usually placed in the separate housing.

Overall achievable precision of the laser micromachining process is not only defined by sensor accuracy of a single axis of positioning mechanism, but rather by the combined effects of guiding accuracy (straightness\flatness), orthogonality and possibly the effects of roll, pitch and yaw on a part to be processed. All these considerations imply the strict design requirements on the mechanical structure of the system.

One of the design requirements of the mechanical structural layout is to maintain the geometrically stable relationship between the workpiece and beam delivery optics during the laser micromachining process. Strict condition of orthogonality between the part surface plane and focusing lens central axis must be satisfied. On the other hand, mechanical stability of laser source is less critical; however the pointing stability of laser must be good enough to ensure reproducibility of beam delivery over long period time.

Final machine performance in general is very much affected by the material selection for a machine structure. When selecting material many criteria are being considered, such as stability, stiffness, homogeneity, easiness of manufacturing and cost, etc.

In conclusion, mechanical design of laser micromachining systems should result in a machine which first of all satisfies the above mentioned design requirements and additionally have characteristics as mechanical simplicity, resulting in ease of maintenance and installation and high reliability.

3.4 Motion Control

Quality and success of laser micromachining process is dictated by three key elements. First key element is the laser, more specifically laser beam characteristics, such as focused beam spot size, beam quality factory and polarization of laser beam. Second key element is the consideration of various physical phenomena occurring due to the laser-material interaction. Third key element is the successful implementation of precise motion control system. This section mainly focuses on the specification of the design requirements for the precise motion control.

Most basic motion control requirements of the laser micromachining system are the utilization of controlled relative motion between the focused laser beam and the micromachining sample in order to micromachine a desired pattern/feature in the material and correct orientation of the desired pattern on the workpiece. Depending on the technique used to perform laser micromachining, relative motion between the laser beam and workpiece can be achieved by moving of the workpiece, moving of the laser beam or moving of both in the same time.

When the relative motion is achieved by moving of the workpiece, the workpiece is mounted on positioning mechanism capable of delivering the desired motion. Most common workpiece positioning mechanisms used for laser micromachining systems are two or three linear axes translational stages, nevertheless the combination of translational and rotational axes stages can be used as well (e.g. the motion stages used in the system for laser micromachining of medical stents). This way of utilization of relative motion is conceptually shown in the Figure 2.1. in previous chapter.

Relative motion by moving of the laser beam can be achieved by translation of laser system together with beam delivery optics that is mounted on a two axes translational stage and having workpiece stationary. Systems constructed in this way allow for very large distances to be covered by laser. This configuration is usually not suitable in laser micromachining systems, because it is difficult to achieve very high precision motion with this kind of systems and usually covering very large distances is not necessary. Another way to achieve the relative motion by moving of the laser beam, more frequently encountered in laser micromachining systems, is the use galvanometric scanner mirrors. The laser beam is reflected off the set of two mirrors providing the positioning of the laser beam in x-y plane. The main advantage of this option is the speed of operation. Galvanometric mirrors are usually moved by electrical or piezoelectric motors. Galvanometric setup is shown in the Figure 3.3.

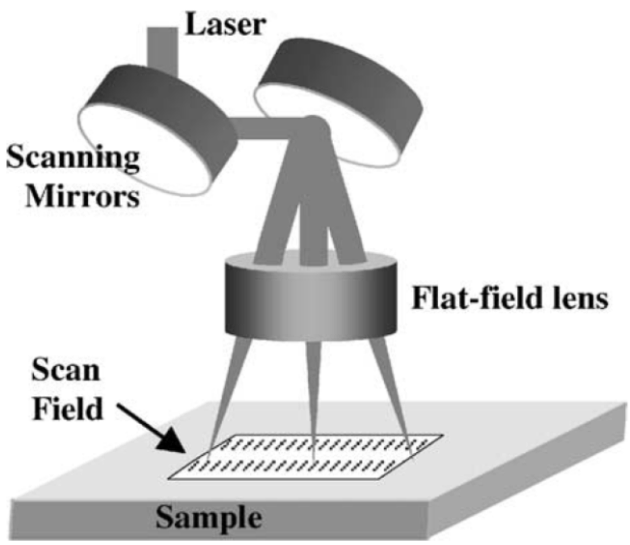


Figure 3.3. – Galvanometric scanner setup [32]

Generally the laser micromachined feature sizes range from few micrometers up to hundreds of micrometers, therefore the positioning capability of an advanced laser micromachining system is required to be in nanometer range. Positioning subsystems must provide nanometer resolution, accuracy and repeatability, along with travels long enough and speeds high enough to permit micromachining process of sufficiently short duration. The successful design of laser micromachining system precise motion control will result in high dynamic contour accuracy, repeatability, speed and a flexible, advanced motion controller. These requirements must be satisfied with careful integration of mechanical, electrical, control and software elements. More specific design requirements for each of these elements are discussed in the following sections.

3.4.1 Positioning mechanism

Laser micromachining applications require fast motion and robust control for precision positioning. Most common workpiece positioning mechanisms in laser micromachining systems are planar x-y stages. The design of such stages is evaluated based on the high performance standards due to the very demanding micromachining accuracy. Overall design success of stages can be evaluated based on proper mechanical design, bearing and actuator technology used and measurement equipment used.

The design of stages can be done in many different ways with respect to mechanical configuration of each axis, nevertheless proper mechanical design should be utilized in order to reduce overall positioning error and uncertainty. Design for this purpose is characterized, primarily, by mechanical simplicity and minimum number of consisting assembly parts. Each next assembly part contributes to overall cumulative geometrical error, arising mostly because of imperfections in mechanical connections. Successful mechanical design of motion stage takes into consideration the capabilities of the equipment on which the stage is machined and defines the strict machining tolerances. Machining error can be greatly reduced by choice of high precision machining equipment and proper part fixturing during the machining. Simplicity of mechanical design contributes to the geometrical error minimization by reducing or completely eliminating the need of part re-fixturing during the machining process.

Another mechanical design consideration of precise positioning x-y stage, and precision instruments in general, is thermal property of construction material. Due to thermal disturbances, in positioning stages generated mostly due to heat input coming from actuator, the thermal expansion will occur. Thermal expansion will cause the mechanical dimension change and consequently have poor effect on overall accuracy.

Selection of bearing technology is very important consideration in the design of positioning stage because bearings define the amount of friction force present during the motion and at rest. Friction force has negative effect on precise positioning and large amounts of friction force prevent the implementation of advanced control algorithms usually required for control of positioning systems in laser micromachining applications. There are many options of bearing selection for precise positioning, but three options prevail in industrial products, namely recirculating ball bearings, anti-creep crossed-roller bearings and air bearings. Recirculating ball bearings are very flexible in the sense of maximum travel and load capabilities, however amount of friction in these bearings limits the precision in positioning down to several micrometers. Crossed-roller bearings are very smooth in operation and when coupled with advanced control system they are capable of nanometer level precision, however no longer travels distances than 30cm are available. Air-bearings can provide near-frictionless motion and bearing geometric performance (pitch, roll, and yaw error motion) is superior to other bearing types. The air-bearing surfaces are large compared to other types.

The linear motion in positioning stages is commonly achieved by either direct drive actuators or actuators based on screw based mechanisms (rotational motor in combination with ball screw or worm gear). There are many advantages of using linear, direct drive actuators in high precision applications in comparison with the traditional screw based drive mechanisms. In the linear direct drive mechanisms the effects of high frictional forces and backlash are eliminated while maintaining high mechanical stiffness. Additionally, the noncontact design of direct drive systems eliminates wear and requires no maintenance. On the other hand, direct drive linear motors have the disadvantage of being more sensitive to the disturbance forces and load inertia variations. This disadvantage has to be taken into account and compensated through a robust and reliable control in order to achieve high speed, high precision motion control. When operating actuators for positioning at micron and submicron levels, any internal disturbances from electrical noise or power electronics that emit electromagnetic noise can cause instabilities and oscillations in the motion system. These disturbance effects can be eliminated by using amplifiers with advanced power electronics design and additional filters if necessary. Two types of amplifiers are commonly used, pulse width modulated amplifiers and linear amplifiers.

Basic requirement of precise positioning are feedback devices with nanometer resolution. The most popular commercial devices capable of nanometer resolution measurement of position are the laser interferometers. Optics required for operation of laser interferometers requires large space utilization, hence the integration is demanding. Position measurement is greatly affected by the environmental conditions such as temperature, pressure and air flow. Due to these reasons other type of feedback devices is preferred, namely linear optical encoders with glass scales. These devices are compact and cost effective. Resolution of optical linear glass scale encoders after interpolation can reach down to 5nm.

3.4.2 Control Requirements

In addition to mechanical design the closed loop control system is utilized in order to achieve controlled positioning and multiaxis contouring. As mentioned in previous sections, laser micromachining requires an advanced motion controller with algorithms and hardware that minimize errors arising due to the disturbances in the system, increase tracking capabilities and provide stability of positioning mechanisms. For the sake of good dynamical behavior of positioning system, the control strategy should be developed such that it matches the dynamics of the mechanical system. Generally the control system uses position feedback, velocity estimation from the position feedback and sometimes for high performance, acceleration feedforward loop. It is commonly believed that the existing control techniques are quite enough to perform motion control assignment for macro and meso parts machining. The stringent requirements for microparts machining require usage of robust control techniques. One such example is Variable Structure Systems (VSS) with Sliding Modes (SM) and Disturbance Observer based compensation. Indeed, most of the systems with closed configuration have nonlinear dynamical models. Therefore, they require a nonlinear control law or a linear control law along with an additional compensation control input obtained from the disturbance observer whatsoever.

3.4.3 Autofocusing

Lasers used in material processing are typically high energy lasers, nevertheless light beam needs to be focused in order to achieve higher energy density and smaller final spot size. Focused laser beam allows processing of smaller features and increases overall quality of the process. Workpieces being processed with laser are not perfectly flat and usually have surface variations that cause change in focus of the laser light and result in uneven processing depth. Remedy to this problem is integration of mechanism that will automatically correct focus by moving lens or workpiece in proper direction. Factors peculiarizing autofocusing systems are speed and repeatability, so processing with same quality can be guaranteed despite of surface variations. Autofocusing mechanisms typically include measurement element, correctional controller and an actuator for the lens.

3.5 Laser System

Most critical component of any laser micromachining system is clearly the laser. After the laser micromachining application has been decided on, a suitable laser source must be selected. In general, any laser micromachining application commonly require certain particular attributes from laser; good beam quality, small focused spot size, high per pulse energy, high pulse repetition rates, short pulse duration, reliability and simplicity of operation with easily controllable system parameters. This section will mainly focus on description of the parameters that play the most crucial role in the selection of the correct laser source for a given laser micromachining application.

Industrial lasers have high capital and operating costs so the selection must be done carefully with respect to laser micromachining application and type of material being processed. Although a laser source is characterized by many parameters, few of the major ones have greater importance on the selection of the appropriate laser, namely, output power, wavelength, temporal and spatial mode and output beam diameter.

Output power is the most basic characteristic of the laser and the main cost contribution factor. Depending on the workpiece material, the design of the laser micromachining system should incorporate laser source with the right output power. Choosing under-powered laser system will lead to increased processing time or inability to machine the desired material, on the other hand choosing over-powered laser system will lead to higher cost of the overall system. Choosing the appropriate laser system requires detailed analysis of micromachining conditions and certain knowledge on laser light – material interaction. Rough estimation of the laser power requirements can be done by examining of specific laser micromachining process model, to relate the material properties and laser operating parameters, however since laser micromachining is still not very established industry estimation of laser power requirements is done based on the experience of the designer.

Lasers can operate in two modes, continuous wave and pulsed mode. In continuous wave operation, the energy is delivered to the material without interruption. In pulsed mode the energy delivery is done in the short pulses (bursts). Both of these modes have certain advantages and disadvantages, pulsed lasers can deliver high instantaneous energy pulses, however they suffer from low average power. Pulsed lasers do not guaranty high quality surface finish, however they are capable of processing difficult to process materials. Processing with continuous wave lasers guaranties high quality surface finish but can cause unnecessary heating up (large heat affected zone) and removal of the non-irradiated regions of the workpiece material. Laser micromachining applications generally require the use of pulsed lasers with short pulse durations and high repetition rates.

Another crucial parameter for the correct laser selection is the spatial mode. This is the parameter that determines the beam profile, i.e. transverse electromagnetic mode (TEM). In simple terms, laser beam mode or profile is the intensity (irradiance or power per unit area) distribution in a plane perpendicular to the beam propagation axis. Beam mode is an indication of how the energy intensity is distributed over the beam cross section. The profile varies with propagation distance from the laser’s output mirror. The fundamental mode has a Gaussian spatial distribution and is generally considered the best for the laser micromachining applications (most of the energy is concentrated in the center of the beam). Laser beam having near Gaussian distribution can be focused to a smaller diameter spot. Beam quality factor (M^2) is the ratio of laser beam’s multimode diameter-divergence to the fundamental beam diameter-divergence product. Minimum value of this parameter is 1 and as the beam quality approaches to this point the spatial distribution is nearer to Gaussian, hence the laser beam has better focus ability. Laser types that have the lowest beam quality factor are fiber lasers.

The wavelength of the laser greatly influences the laser micromachining process primarily due to the laser-material interaction consideration. Shorter wavelength lasers are more advantageous in laser micromachining because materials are processed by a relatively cold ablation process, in other words at shorter wavelengths photons posses higher energy and they break atomic and molecular bonds to remove material. On the other hand the lasers with longer wavelengths process material thermally with localized intense heating and boiling process. Shorter wavelength lasers can be focused to smaller spot sizes.

Most commonly used laser types for laser micromachining applications are Nd:YAG solid state lasers (1.06 or 0.355 microns wavelength), pulsed or continuous wave CO2 gas lasers (10.6 microns wavelength), excimer lasers with nanosecond pulses (248 or 193 nm wavelength). All of these mentioned lasers are operated in a pulsed mode to achieve best machining quality. The focus ability of the CO2 lasers is an issue and drawback due to the long wavelength so these types of lasers are not used in applications requiring very small feature sizes. Looking from the cost-effectiveness point of view the excimer lasers are the best, however they suffer from low repetition rate and poor beam quality. These disadvantages are greatly affecting the performance of the excimer lasers in direct write processes, nevertheless they are most commonly used lasers for mask projection technique.

Above mentioned lasers are lasers characterized with relatively long pulse durations. Lasers with ultrashort pulse durations (pico and femtosecond lasers) have been developed recently and they found place in many micromachining applications. Lasers with ultrashort pulse durations are usually characterized with extremely high peak pulse power; as a result they are less dependent on the absorption effects and can machine most substrates. Ultrashort pulsed lasers are as well associated with no heat generation in the target material during the pulse duration so the secondary effects of the laser micromachining such as thermal damage, recast and debris are avoided. These lasers are still relatively expensive.

3.6 Beam Delivery Optics

The beam delivery optics for laser micromachining purposes consists of optical and opto-mechanical components that serve the purpose of focusing of the laser beam onto the workpiece surface. The major components of the of the beam delivery system are mirrors, focusing lenses, beam expanders, beam splitters and fiber optic couplings. Use of proper beam delivery optics can greatly improve the micromachining quality. This section deals with the description of beam delivery system components and some of the design/selection criteria for these components.

The main design/selection criteria for the mirrors used in the laser micromachining systems are the high surface reflectivity and ability to withstand high energy densities without sustaining thermal damage. Metallic mirrors are generally used in laser micromachining beam delivery systems. Metallic mirrors can withstand high energy densities without the thermal damage due to high thermal conductivity of most metals. The most widely used metal for the mirrors is copper. Copper surface is additionally coated in order to make it hard, easy to clean and prevent oxidization. Mirror surface is additionally diamond-polished to increase the flatness.

Focusing lens is used to concentrate the laser beam into a small spot with high power/energy density. The main design/selection criteria for the focusing lenses used in the laser micromachining systems are transmissivity at the laser light wavelength, minimum achievable spot diameter and depth of focus. While the first criterion is determined during the production of the lens, the minimum achievable spot diameter and depth of focus depend on many parameters. Both of these criteria are of significant importance since they are the factors directly affecting the micromachining resolution. Spot diameter and depth of focus are given by the following relationships:

$$d = \frac{4\lambda f}{\pi W} \tag{3.1}$$

$$b = \frac{2\lambda f^2}{\pi W^2} \tag{3.2}$$

d is the focused spot diameter and b is the depth of focus that defines the working range for laser micromachining. λ is the beam wavelength, W is the diameter of unfocussed beam and f is the focal length. These formulas are valid under the assumption that the beam's energy distribution is Gaussian and beam has single wavelength. Otherwise the aberration limitations should be taken into account.

As it can be inferred from the above equations there is a trade-off between the minimum achievable spot diameter and the depth of focus, hence the working distance. In order to choose appropriate focusing lens to be used in the laser micromachining system, attention should be paid to the parameters defining this trade-off. Increase in the focal length results in the increase of the working distance, however the spot diameter also increases thereby reducing power density. For laser micromachining of very thin workpieces, it is advisable to use minimum focal length in order to decrease the beam diameter and increase the energy/power density which results in maximum material removal rate with very high resolution patterns. For a given laser beam wavelength, the spot diameter can be decreased either by decreasing the focal length or by increasing of the unfocussed beam diameter.

Beam expanders are optical components containing number of lenses and mirrors that are used to increase the unfocussed beam diameter. There are two types of beam expanders; transmissive and reflective. Mainly beam expanders are designed such that the energy/power loss is minimal. The main selection criterion of the beam expander is the magnification ratio, or the relationship in the waist diameters of the incoming and outcoming beams. The straightforward relationships described in previous two paragraphs are depicted in the Figure 3.4. The figure is not to scale.

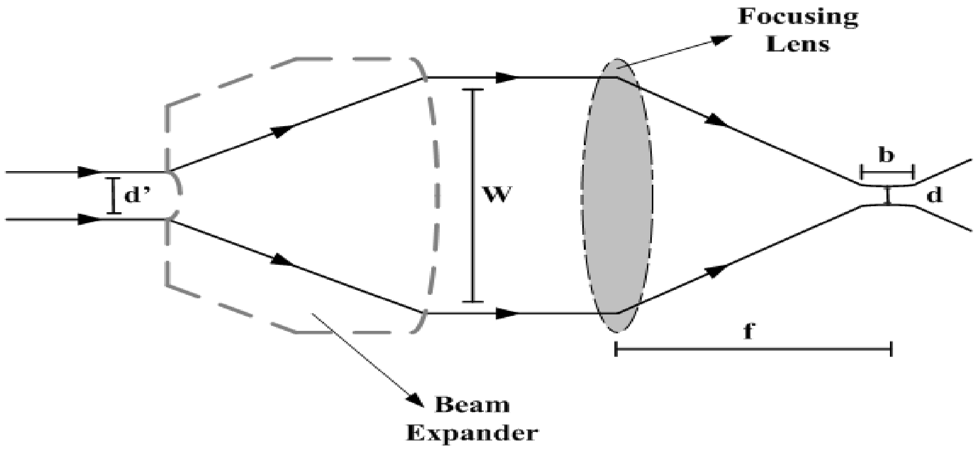


Figure 3.4. – Beam Expander and Focusing Lens

The beam splitter and the fiber optic couplings are not necessarily key optical components for the beam delivery system. The beam splitter is flat optical device that is designed in such a way to reflect the part of the incident beam energy while transmitting the remainder. If the vision system is incorporated together with beam delivery optics, depending on the orientation configuration of the optics beam splitter comes to play important role. The fiber optic coupling is used in the micromachining system where higher degree of mechanical design flexibility is needed. Coupling laser light with fiber optic cable can be used instead to the mirror assemblies decreasing the beam delivery complexity significantly. The limiting factor in the fiber optic coupling is the beam power that can be transmitted, up to 500W for the pulsed lasers.

3.7 System Controller and MMI

Laser micromachining system has a multidisciplinary nature. Indeed, it is a mechatronic product with a material science oriented applications. In other words, such system has to meet requirements such as the ability to alter various process parameters, namely, laser, material and motion parameters, so as to make it possible to investigate some material science phenomena's or micromachining phenomena. Depth of cut, feed rate and many other parameters influence the outcomes of the micromachining process.

However, the ability to alter these parameters is mainly achieved by motion control of proper mechanical system. Consequently, an interface with the system has to be available to allow a researcher or an operator to obtain desired outcomes by varying the necessary parameters. Similarly, laser parameters along with material type are of a great concern to any material science oriented research. Therefore, an interface between the system and user has to include the ability of varying such parameters as well. Besides, monitoring of the entire process also has to be considered that can be partially developed using a visual system to enable user to monitor the ongoing process. Software design should contain simple user interface and job loading to simplify work set up and increases productivity. The user interface should allow easy design or import of patterns, flexible modification and possibly simulation of micro machining process.

The features of the system controller are significant factor affecting the success of the laser micromachining system operation. The main requirements of the overall system controller are the ability to:

- Provide accurate positioning of the workpiece
- Provide the reliable and fast tuning of the laser parameters
- Synchronize the movement of the workpiece and the delivery of laser pulses
- Interface the user with the machine
- Monitor the overall system and provide reliable control of auxiliary devices

System controller has to incorporate high precision and high quality electronic hardware equipment and be able to satisfy the computational requirements of the control algorithms. Controller hardware is usually designed with combination of digital signal processor (DSP) and field programmable gate array (FPGA) devices. Controller peripheral devices such as analog-to-digital (AD) converter, digital-to-analog (DA) converter, position encoder interpolators and digital I/O's are responsible for supplying voltage references to drive electronics and position and process data collection from plant. Precise motion control requires high resolution and high speed operation of DA convertors is order to be able to precisely interpret the voltage references supplied to the amplifier and drive electronics. Commonly the DA convertors with more than 16 bits of resolution and short conversion cycles are used. High resolution of position encoder interpolation electronics is another crucial consideration. These devices should incorporate data collection registers of 32 bits and more, especially in the cases when collecting encoder data from positioning mechanisms with long travel range and high resolution encoders.

Overall control system should include the non real-time tasks needed to determine the motion of the sample and the parameters of the laser source. The overall structure of the controller is depicted in Figure 3.5.

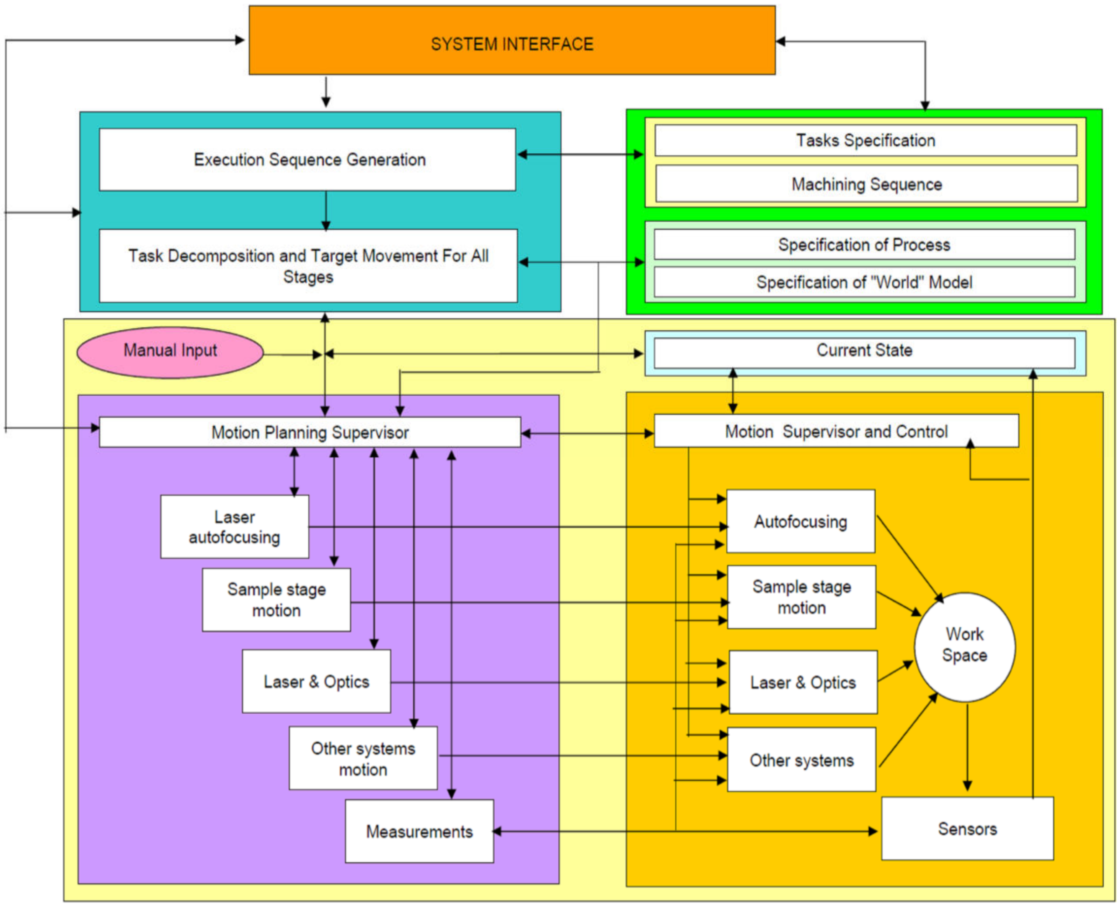


Figure 3.5. – Overall System Controller

3.8 Summary of the design requirements

The overall system motion, controller, laser and beam delivery optics design requirements are summarized in this section. In order to give overview and define the design requirements numerically, tables with the desired values or limits of the design variables are shown and some additional information is given.

3.8.1 Motion Design Requirements

Mechanical Specifications (unit)	***Value***
Travel- x direction	65 mm
Travel- y direction	65 mm
Travel- z direction	150 mm
Resolution- x direction	< 0.1 µm
Resolution- y direction	< 0.1 µm
Resolution- z direction	< 0.1 µm
Maximum speed- x and y directions	> 100 mm/s
Maximum speed- z direction	> 4 mm/s
Maximum acceleration- x and y	> 5 m/s^2
Load capacity- x direction	2 kg
Load capacity- y direction	1 kg
Load capacity- z direction	12 kg

Table 3.1. – Overall System Motion Requirements

Due to the non-contact nature of the machining process, the maximum load capacities of the motion stages are not very large compared with the ones utilized for contact machining. The speed and acceleration of the motion stage are selected such that the control system has the ability to synchronize the motion of the end effector with the pulsation rate of the laser source. Resolution of the motion stage is much related to the minimum spot that can be obtained by focusing the laser beam.

The third degree of freedom is required in order to perform three tasks, namely, allowing the system to micromachine multiple layers, keeping the focus constant throughout the entire machining process and adjustability to positioning mechanism of different height profiles. The first one is a very conventional requirement of any motion stage. The second requirement is strongly needed in any laser micromachining process due to the possible surface variation of the workpiece which in turn changes focus that is required to be constant throughout the whole machining process.

3.8.2 Controller Design Requirements

Hardware Specifications (unit)	***Value***
Controller Processor Speed	> 1 GHz
DA Resolution	≥ 16 bits
DA Conversion Time	< 1.5 μs
DA Output Voltage Range	-10V…10V
AD Resolution	≥ 14 bit
AD Conversion Time	< 1.5 μs
DA Output Voltage Range	-10V…10V
Encoder signal type	Digital
Position Counter Size	32 bits
Encoder Sampling Frequency	> 1 MHz
Digital I/O Signal Type	0…5V TTL
Communication Interface	Ethernet, RS232 USB, PCI, Custom

Table 3.2. – Overall Controller Hardware Requirements

A specification such as number of DA/AD converter and digital I/O channels is specified according to the selection of laser equipment and the interface specifications of the laser controller equipment. This specific requirement is best to be selected after the selection of laser is done. Since the first prototype implementation of the laser micromachining system is planned to be performed on some type of prototyping controller hardware with large number of AD, DA and digital I/O channels, this is considered not to be concern.

The communication interface is required in order to transfer the data such as motion references or laser parameters settings from the controller hardware to PC and to read and display data collected by controller hardware on the PC screen. This communication can be decided on the preference of the designer depending on the availability of components and easiness of programming.

3.8.3 Laser System and Beam Delivery Optics Design Requirements

Laser and Optics Specifications (unit)	***Value***
Laser Type	Fiber
Laser Power	> 15 W
Laser Pulse Duration	< 100 ns
Laser Mode	Pulsed
Beam Quality Factor (M^2)	< 5
Raw Beam Diameter	< 2 mm
Lens Focal Length	< 100 mm
Lens Clear Aperture (CA)	> 15 mm
Focused Beam Diameter	< 15 µm

Table 3.3. – Laser System and Beam Delivery Optics Requirements

The laser system design requirements are listed in Table 3.3. Type of the laser is required to be fiber, due to the extremely low beam quality factor and flexibility of installation. The laser wavelength is not specified because this parameter is decided related to the material type and laser micromachining process. In general this parameter is favorably small due to the better focusability of the laser beam with shorter wavelength (see Eq. 3.1).

Last two rows of the Table 3.3. are related to the design requirements of beam delivery optics. Looking at the raw beam diameter and lens clear aperture the design requirements for the beam expander can be decided upon.

4 SYSTEM IMPLEMENTATION

4.1 Introduction

This chapter presents the design and implementation of laser micromachining system. The design requirements discussed in Chapter 3 are satisfied and the details about their implementation are given here. In general this chapter discusses the puzzles related to the selection of proper building components of laser micromachining system, detailed mechanical design concepts, precise control issues in positioning mechanism and the configuration of the overall system.

Laser micromachining system presented in this chapter is a complex mechatronics system designed for research purposes in advanced laser micromachining techniques and development of industrial application devices and components. The developed system combines precision mechanical design, advanced control strategy and high level of user interaction. The system is designed as a general purpose laser micromachining system, however throughout the chapter certain aspects of easy customization possibility of this system to a large number of different laser micromachining applications will be discussed. Main reason for easy customization possibility of the designed system is the design philosophy that has been utilized. Design philosophy for laser micromachining system was to maintain simplicity of design and achieve the modularity on both, system and component level while preserving full functionality of the overall system.

4.2 Overall System Configuration

Designed and developed laser micromachining system in shown in the Figure 4.1. This is direct write laser micromachining system capable of performing many micromachining tasks such as microscribing, ablation, Si processing, resistor trimming, solar cells processing, thin film cutting, micromarking, etc. The system utilizes nanosecond fiber laser as the energy source, beam delivery optics, x-y planar positioning mechanism, controller and personal computer.

The operation of the system can be described as following; the laser produces and outputs the pulsed beam with desired temporal, spatial and energy characteristics; pulsed laser beam passes through beam delivery optics, consisting of beam expander, series of beam splitter and focusing lens; workpiece is fixed on top of the x-y planar positioning stage which is controlled by controller to deliver motion sequence in order to produce the desired micromachining feature; controller supplies the stage drivers with voltage references, adjusts the laser pulse characteristics and synchronizes the laser pulses with motion; personal computer contain the graphical user interface and serves the purposes of inputting technical drawings, setting of laser parameters and process monitoring. This laser micromachining system indeed satisfies all of the functional requirements listed in section 3.1, namely:

- The machine is capable of providing means for removal of material from workpiece using laser micromachining process.
- Relative motion between the workpiece and laser beam is utilized such that laser beam is stationary and workpiece is moving to produce desired feature in material.
- The configuration of designed system utilizes three-degree-of-freedom relationship between the laser beam and workpiece and this relationship is fully programmable using computer and controller.
- Laser beam has the access to the entire workspace of the positioning mechanism. Positioning mechanism has long motion travel with nanometer level motion resolution.
- The orthogonality between the workpiece fixture and laser beam central axis is guaranteed by the mechanical design.

- The interface with automatic workpiece loading system is achieved by the positioning stage translation mechanism and as such this system can be used as the part of industrial production facility.
- Software and MMI of the designed system provides easy and user-friendly way of interaction with the laser micromachining system. This interaction consists of laser parameter setting, technical drawing input, monitoring of the process and emergency stop actions.
- Presented laser micromachining system operates on standard utility, has small footprint, low mass (about 35kg) and is easy to transport.

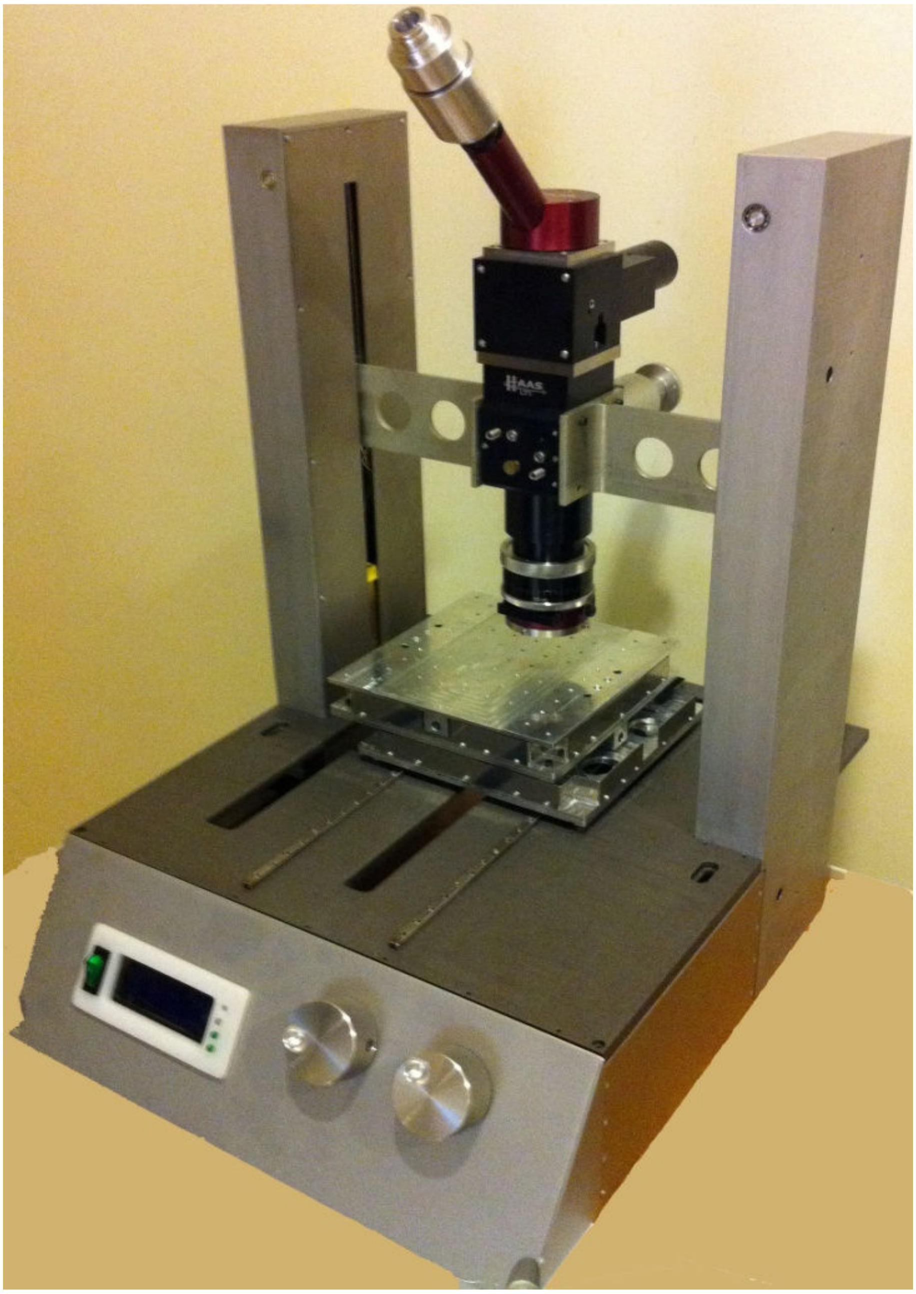


Figure 4.1 – Laser micromachining system

4.3 Mechanical Structure

The mechanical structure is depicted in Figure 4.2. and corresponding mechanical sub-modules are numerically labeled. When referred to these modules in the rest of the text, the corresponding numerical label will be placed in parenthesis. The mechanical structure of laser micromachining systems consists of machine base and column (4), optics head lift mechanism (2), planar x-y positioning stage (1) and positioning stage translation mechanism (3).

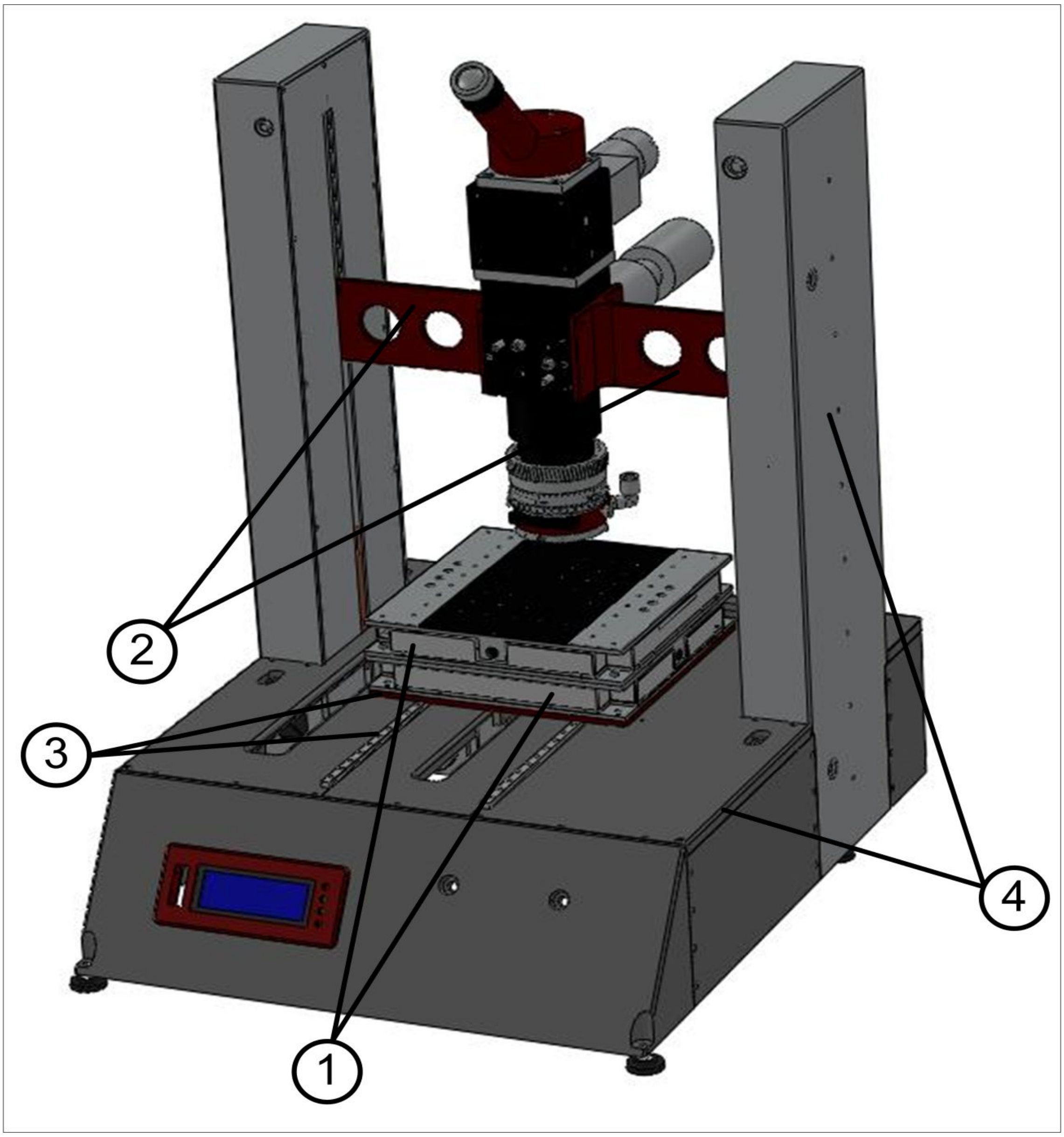


Figure 4.2. – Mechanical structure of laser micromachining system

In overall, system has four degrees-of-freedom; two are achieved by planar x-y positioning stage (1) responsible for workpiece positioning under the laser beam, beam delivery optics is positioned to desired vertical distance inside the maximum travel by optics head lift mechanism (2) delivering single degree-of-freedom motion and the final degree-of-freedom is delivered by positioning stage translation mechanism (3).

Integration of complex and demanding modules needed for proper operation of a laser micromachining system requires the design of mechanical support structure that contains the modules such as the laser system, beam delivery system, planar x-y positioning stage, overall system controller and personal computer with man machine interface. The design of mechanical structure satisfies the design requirements discussed in Chapter 3. In particular, the design satisfies high precision motion requirements, accuracy, flatness over a motion range and repeatability with focus on force and stress analysis requirements, ease of the assembly, robustness and manufacturability. It is worth noting that due to the superior performance that has to be achieved in terms of motion requirements, in addition to the unavoidable weights and inertias of standalone out of the shelf products, the mechanical design turned out to be a key feature and a major component that had to be considerably handled.

As discussed earlier the accuracies of mechanical mating parts affect the overall accuracy of the system and therefore laser micromachining process. As a remedy, kinematical inaccuracies can be reduced during the design, machining and assembly stages of the overall system. Therefore, the system is designed such that minimum components have to be manufactured while maintaining the full functionality. Consequently, minimum machining tolerances and minimum assembly errors are induced in the laser micromachining system. In addition, the mating parts of the mechanical structure are firstly machined individually, assembled and then re-machined together in order to avoid any cumulative machining tolerances. Such machining and assembly process of mechanical structure guaranties the orthogonality between the machine base surface and the laser beam central axis. Nevertheless, assembly error and manufacturing tolerances are present between the optics head nozzle and the surface of the vertical stage, since the surface of the optics head lift mechanism and the top plate of planar x-y positioning mechanism are not machined simultaneously. These two sensitive surfaces were not machined simultaneously due to the fact that there exists a relative motion for each of these surfaces with respect to the column and the base of the system, respectively. Relative motions of each of these parts require utilization of sensitive mechanisms such as rails and carts with very low friction. That in turn would result in vibratory response of their elements when the cutting tool comes into contact with the surface during the machining. These chattering would cause undesired surface roughness and waviness due to the lack of rigidity during machining.

4.3.1 Optics Head Lift Mechanism

In order to assure the focal spot of the laser to be exactly on the workpiece top surface, hence to achieve maximum micromachining resolution, optics head lift mechanism has been designed to translate the optics head to the desired vertical distance above the workpiece. The optics head mechanism is shown in the Figure 4.3. with corresponding numerical labeling of the sub-modules. The optics head (1) is fixed via two brackets with respect to two stationary columns (2). Each of these columns contains a counter weight (3) attached to the brackets via pulleys. Total mass of weights counters the mass of the optics head along with its attached components. Such mechanism allows utilization of actuator with lower load capacity and prevents the unnecessary heat dissipation in actuator. The optics lift mechanism is driven by the belt (4) which is actuated by DC motor with a gear box (5) that is contained in the bottom base. A belt drive (4) is utilized in order to transmit the motion from the gear box at the base to the driven pulley which moves the laser head in a vertical direction through brackets.

The implementation of the optics head mechanism is important from the point of view of modularity and easy customization ability of the laser micromachining system. Due to this mechanism, the workpiece height profile is not limiting issue for performing of laser micromachining. Depending on the requirements of the laser micromachining application the positioning mechanism can have kinematical configuration other then the planar x-y positioning stage and can have different height profiles. Optics head lift mechanism provides adjustability of the height of optics head so that application required positioning mechanism can be mounted beneath it. Design done in this way allows for quick, task specific customization of laser micromachining system and eliminates the remanufacturing costs of mechanical structure.

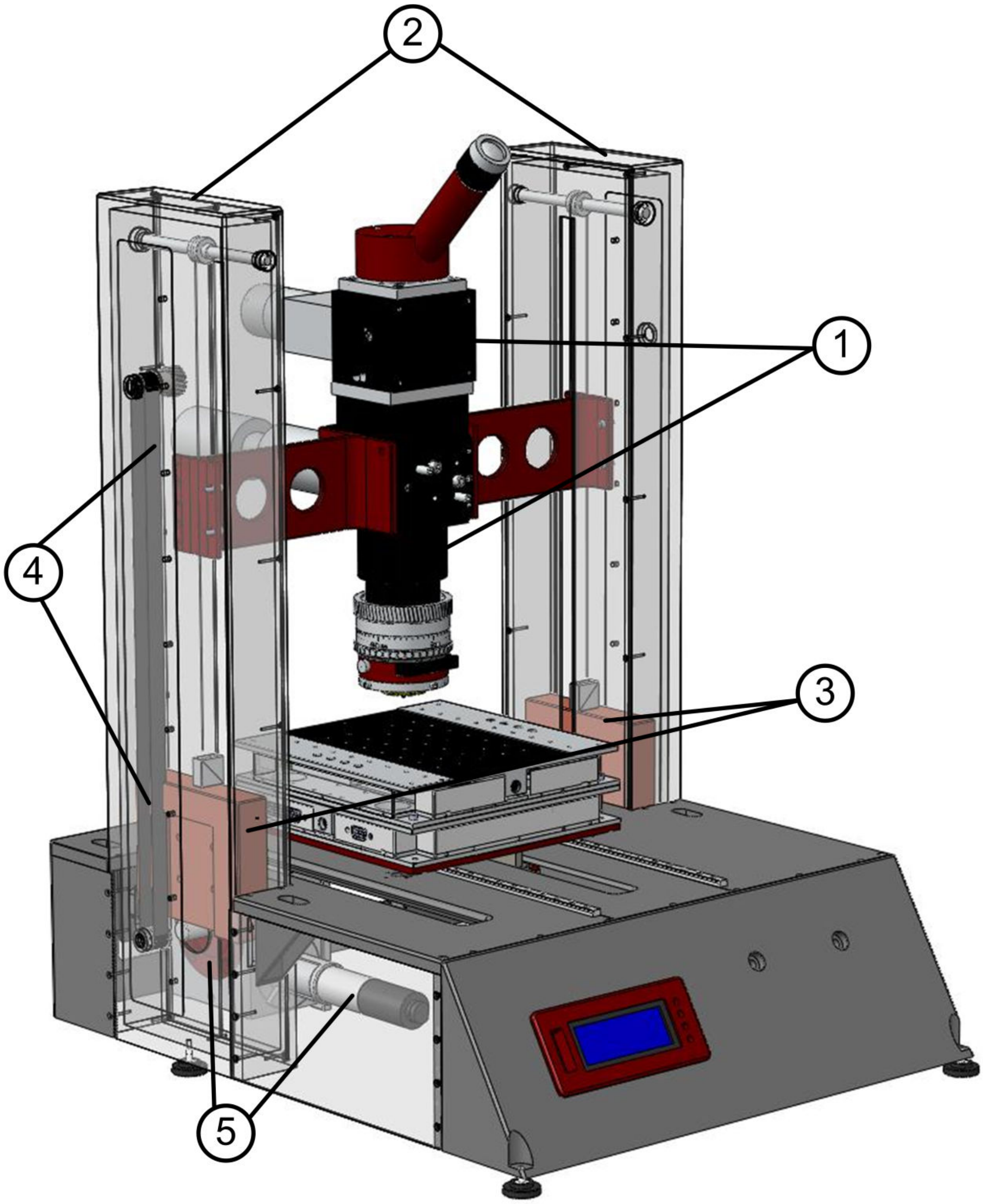


Figure 4.3. – Optics head lift mechanism

4.3.2 Positioning Stage Translation Mechanism

There are two reasons for the design of such mechanism; to allow the system operator insertion and fixing of the workpiece onto holder in ergonomic fashion and if the system is to be used as a part of industrial production facility, to allow for easy workpiece loading action. The mechanism is interfaced with the system controller and can be easily automated. The positioning stage translation mechanism is depicted in Figure 4.4. with corresponding numerical labeling of the sub-modules. The planar x-y positioning stage is fixed on a movable plate (1) which allows the user to automatically move it to a position at which material can be loaded or the finished micromachined workpiece removed. The motion is achieved though the double rails (2) mounted on the main base. These rails allow the movable plate (1) attached to the positioning mechanism to slide back and forth. The movable plate (1) is attached to a rack (3) and driven via a pinion (4) that is placed inside the bottom base and actuated by geared DC motor (5). Controlling the motion of mechanism can be done manually or through the software.

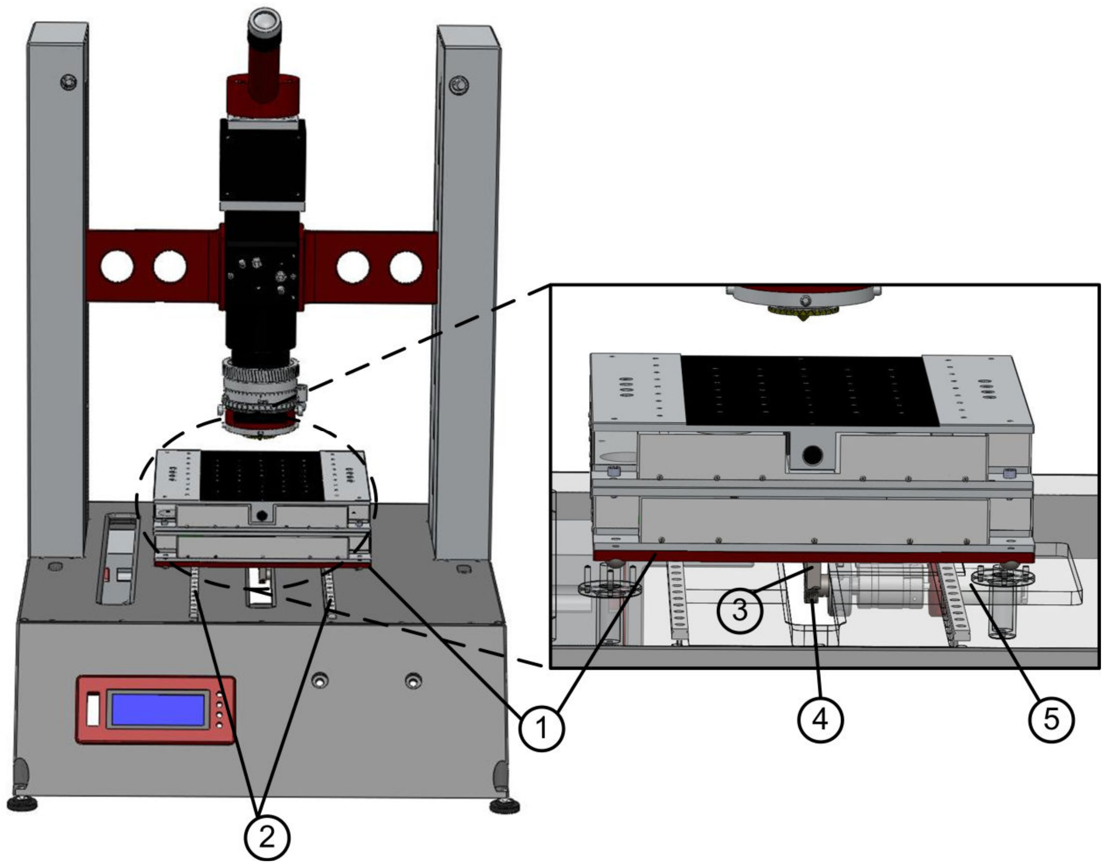


Figure 4.4. - Positioning stage translation mechanism

4.4 Motion Control

In this section the design implementation of motion control part of the laser micromachining system is discussed. The discussing focuses on the x-y planar motion stage design, motion planning and control algorithms, the controller structure and the autofocusing system implementation.

4.4.1 X-Y Planar Motion Stage

In order to meet the requirements of the precise positioning of the workpiece during laser micromachining process, custom 2 axis fast and precise motion stage is designed and realized. The 2 axis positioning stage is shown in the Figure 4.5. and stages technical specifications are listed in Table 4.1.

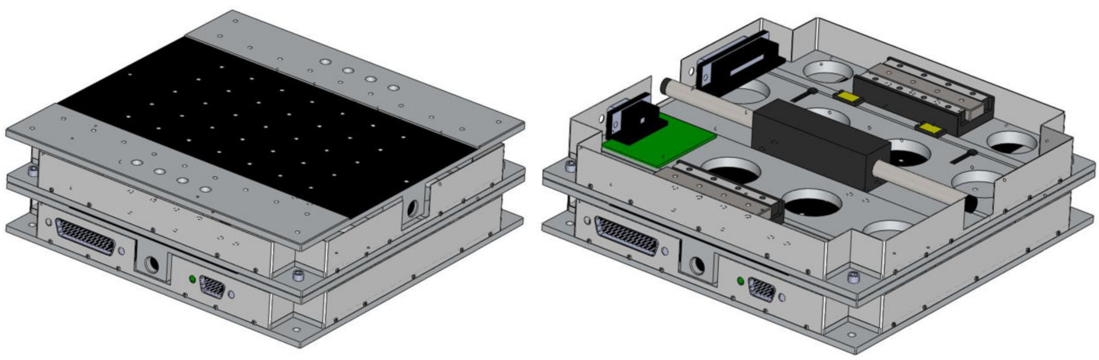


Figure 4.5. – Planar x-y positioning stage

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

Table 4.1. – Technical specifications of planar x-y positioning stage

Motion stage consists of two identical stages, each providing motion in a single axis. The design of each of the stages is characterized with the minimum space consumption, simplicity and modularity. Special attention is paid to the simplicity of the design. The mechanical structure of the individual stages is composed of minimum number of assembly parts, but still provides full functionality of the stage. There are two advantages of such design; the geometrical errors, usually arising during the machining of complex parts are minimized and mechanical assembly errors are minimized.

As an actuator for each axis of the stage brushless, high-precision direct drive linear servomotors are used. The direct drive linear servomotor was chosen for the design because it is a simple, highly efficient and high precision motor that requires no maintenance over its lifetime. There are many advantages of using linear, direct drive motors in high precision applications in comparison with the traditional gear-reduced drive mechanisms. In the linear direct drive mechanisms the effects of high frictional forces and backlash are eliminated while maintaining high mechanical stiffness. This particular motor consists of two parts, a magnetic shaft and a forcer of wound coils. The absence of iron in the forcer or shaft results in the ultra high precision and very low cogging force. Each axis of the motion stage incorporates position measurement embedded in its mechanical structure. Position feedback is obtained from a high grade analog optical encoder in conjunction with an efficient interpolator. In addition to the direct drive actuator and position sensor, roller cage linear slides are used to provide linear motion in all three stages. These linear slides are designed specifically for highest accuracy requirements and have very low friction force.

The efficient workspace of the x-y stage is 65x65mm which fulfils the requirements of the laser micromachining of relatively big workpieces, however the same technology can be scaled up to be used for the applications that require larger workspace, the only limitation is the travel range of the linear slides. Commercially available roller cage linear slides come in options with maximum travel up to 300mm.

4.4.2 Motion Planning and Control Algorithm

Laser micromachining applications require the micromachining of complex geometry features in different materials. These features are usually drawn using technical drawing software such as AutoCAD or SolidWorks. This section elaborates on technique for processing of files containing geometrical description of features to be micromachined and translation of those descriptions to position, velocity and acceleration references for the positioning mechanism to follow. Further, specific method for obtaining of those references is described and model and control strategy for the precise positioning mechanism is developed. Experimental results are given in the next chapter.

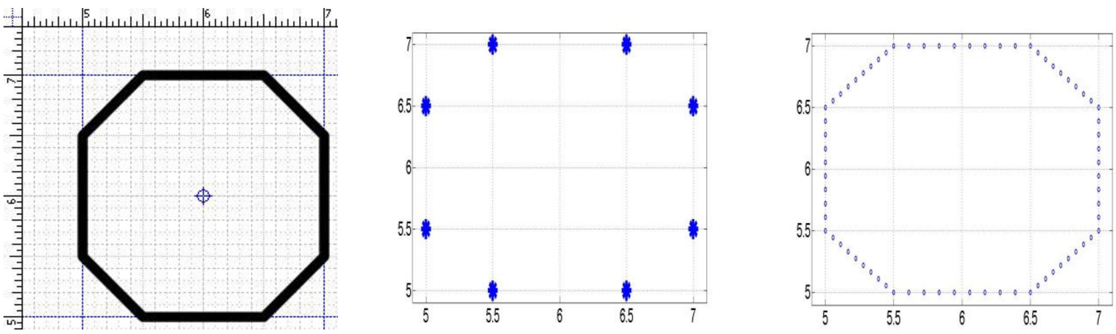
4.4.2.1 Technical drawing file processing

File containing the geometrical description of the part to be machined is chosen to be the drawing exchange format .dxf. dxf format is tagged data representation of all the information contained in a technical drawing file. Tagged data means that each data element in the file is preceded by an integer number that is called a group code. A group code's value indicates what type of data element follows. Virtually all user-specified information in a drawing file can be represented in dxf format. dxf is universal in a sense than it can be generated with many different technical drawing software such as Catia, SolidWorks, AutoCAD, Adobe Illustrator or Microsoft Office Visio.

The dxf file is an ASCII version file. The basic organization of a dxf file is as follows [36]:

- *Header section* - General information about the drawing
- *Classes section* - Holds the information for application-defined classes whose instances appear in the BLOCKS, ENTITIES, and OBJECTS sections of the database
- *Tables section* - This section contains definitions of named items.
- *Block* section - This section contains block definition entities describing the entities comprising each block in the drawing.
- *Entities section* - This section contains the drawing entities.
- *Objects section* - Contains the data that apply to non-graphical objects.
- *Section* – contains the preview image of dxf file
- *EOF* – end of file

Parsing of the dxf file is done by parsing of the corresponding text file. Crucial information about the geometry of the drawn part is contained in aforementioned *entities* section. Subsections of the *entities* are identifying the type of the shape used to draw the part. Some subsections are; *circle* (identifying circular shape), *line* (identifying line), *lwpolylıne* (identifying any close structure containing more than two lines*), ellipse* (identifying ellipse), etc. The information contained in these subsections is essential data necessary to identify specific shape. After parsing of dxf file is done the coordinate points of the specific feature are then post processed and interpolated in order to increase the number of points describing the feature. Figure 4.6. depicts drawing of the feature, parsed version and interpolated version of it. In order to increase the number of points between the distinct coordinate points obtained by parsing, interpolation methods are used. Interpolation can be done by curve fitting of line, circle, ellipse or arc.



(a) Part drawn by technical drawing software

(b) Coordinate points of the part after parsing

(c) Data points after the interpolation

Figure 4.6. – dxf file processing and interpolation steps

4.4.2.2 Time Baser Spline Approximation

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. Trajectory generation algorithm satisfying these requirements is determined to be time based spline approximation in combination with efficient controller [37, 38, 39]. 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. As described in [37] the procedure for performing of the time based spline approximation is as follows;

- assuming the geometrical description of the path is supplied, the displacement to be covered in one sampling interval is determined for a given tangential velocity;
- the x-y trajectory is divided into coordinate points whose separation distance is determined in the previous step;
- time based spline approximation is executed using coordinates of division points.

Spline approximation is done using following polynomial equation for position expression:

$$x = \alpha_x t^3 + \beta_x t^2 + \gamma_x t + \delta_x$$
$$y = \alpha_y t^3 + \beta_y t^2 + \gamma_y t + \delta_y \quad (4.1)$$

The displacement moved in one sampling interval can be calculated from given velocity profile as

$$\Delta L = V \times T_s \quad (4.2)$$

As shown in Figure 4.7., x and y values in each sampling time are the coordinates of dividing points on the given geometrical trajectory by ΔL distance.

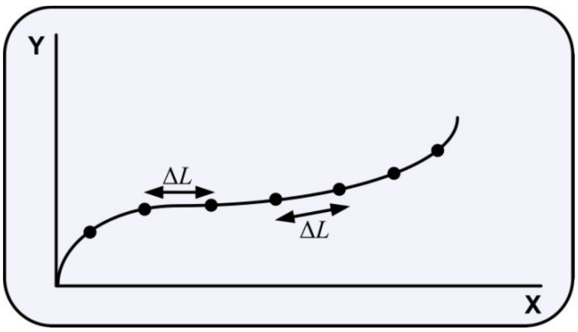


Figure 4.7. – Time based spline approximation curve division

The equation (4.1) represents the projection of the geometrical function into time domain function. Coefficients $\alpha, \beta, \gamma, \delta$ can be calculated using equation (4.3).

$$\boldsymbol{C}_x = \boldsymbol{T}^{-1}\boldsymbol{X}$$
$$\boldsymbol{C}_y = \boldsymbol{T}^{-1}\boldsymbol{Y} \tag{4.3}$$

Where $\mathbf{C_x}$ and $\mathbf{C_y}$ are 4x1 vectors of calculated coefficients, **X** and **Y** are 4x1 vectors containing previously determined coordinate points, **T** is the sampling time 4x4 matrix. The calculation of the coefficients is done by using sliding window containing 4 coordinate points, i.e. in order to calculate the coefficients for the current position point described by the Eq. 4.1, the information of that and the next three coordinate points are needed. 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 [37]:

$$\mathrm{x_n}(t_n) = \alpha_n \mathrm{t_n^3} + \beta_n \mathrm{t_n^2} + \gamma_n t_n + \delta_n$$
$$\dot{\mathrm{x}}_\mathrm{n}(t_n) = 3\alpha_n \mathrm{t_n^2} + 2\beta_n \mathrm{t_n} + \gamma_n$$
$$\ddot{\mathrm{x}}_\mathrm{n}(t_n) = 6\alpha_n \mathrm{t_n} + 2\beta_n$$
$$n = 1 \dots k \tag{4.4}$$

where k is the total number of coordinate points. The similar equation can be written for position, velocity and acceleration in y direction.

Time based spline approximation guaranties the constant tangential velocity throughout the path since the displacements covered in sample time step are of the same size. This fact goes into favor to laser micromachining application where the constant processing depth is desired. Keeping the tangential velocity constant in combination with constant laser power will result in constant processing depth with lasers.

4.4.2.3 Modeling and control of planar x-y positioning 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

$$M_n\ddot{x} + F_l(x, \dot{x}, t) = K_{fn} i \tag{4.5}$$

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, $x, \dot{x}$ and $\ddot{x}$ 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. Controller design for trajectory tracking control and contouring control differ from each other. Nevertheless, in the case of planar stage high contouring performance can be achieved by designing an efficient trajectory tracking controller for each axis separately.

In order to achieve high precision motion control, the controller has to be designed to both impose the desired acceleration to the plant and compensate for the nonlinear disturbance forces effects. The desired acceleration can be calculated using the acceleration, velocity and position references previously found using time based spline algorithm.

$$\ddot{x}_d = \ddot{x}_{ref} + K_v(\dot{x}_{ref} - \dot{x}_{fb}) + K_p(x_{ref} - x_{fb}) \tag{4.6}$$

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

Since the reference acceleration, velocity and position are previously known a form of feedforward compensation can be applied as described in [37, 38, 39], where the reference position command is supplied to the control system at a current sampling time, velocity reference command is supplied one sampling time ahead and acceleration reference command is supplied two sampling steps ahead.

As mentioned before another task of the controller is to compensate for the disturbance forces acting on the input of the plant. Disturbance forces are the sum of static and dynamic friction forces, disturbance forces arising from unequal magnetic attraction between the forcer and stator, cable bias forces, ripple force arising from the load mass and motor force constant variations and the rest of nonlinear disturbance forces. Estimation of the disturbance force can be done using the second order low pass filter and information of reference input current and position feedback [42] as follows:

$$i^{dis} = \frac{g_1}{s^2+g_2s+g_1}\left(i^{ref} - \frac{M_n}{K_{fn}}s^2x_{fb}\right) \tag{4.7}$$

$$F_l = K_{fn}i^{dis} \tag{4.8}$$

where g_1 and g_2 are positive coefficient determining the cutoff frequency of the lowpass filter. Finally we can write the expression for the current i supplied to the motor:

$$i^{ref} = \frac{M_n}{K_{fn}}\ddot{x}_d + \frac{g_1}{s^2+g_2s+g_1}\left(i^{ref} - \frac{M_n}{K_{fn}}s^2x_{fb}\right) \tag{4.9}$$

The block diagram of the overall control scheme is shown in the Figure 4.8.

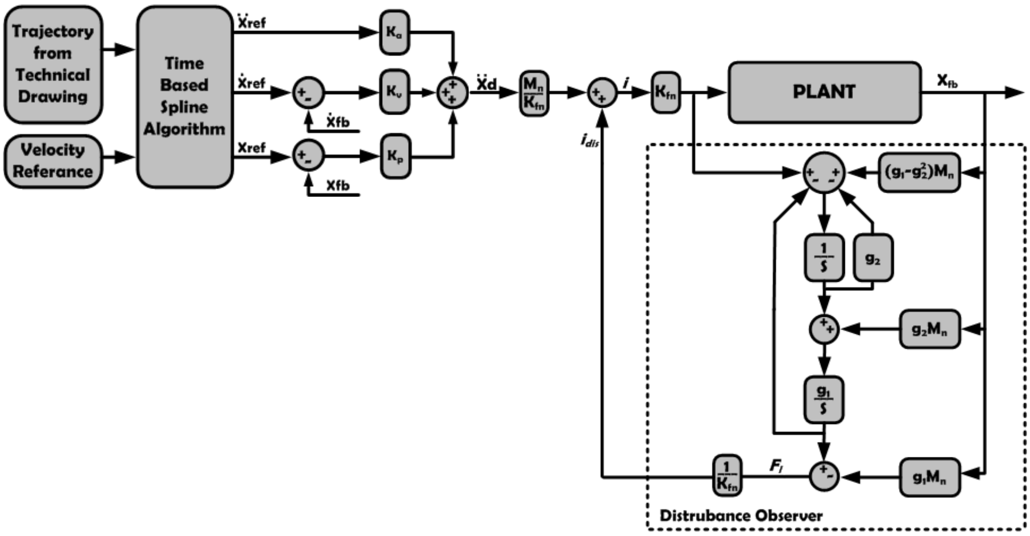


Figure 4.8. – Controller Block Diagram

4.4.3 Controller Hardware

Currently system is controlled by the modular Dspace control system DS1005 that features a PowerPC 750GX processor running at 1 GHz and DA/AD cards, encoder signals processing cards and digital I/O cards. The specifications of the control hardware together with peripheral devices are given Table 4.2. Dspace control system is used for the first prototype development and will not be used in the final version of the system mainly due to the economical considerations. The design of the new control hardware is discussed in Chapter 6 as future work. System features personal computer that runs on Windows XP.

Hardware Specifications	***Value***
Controller Processor Speed	1 GHz
DA Resolution	16 bits
DA Conversion Time	1.1 μs
DA Output Voltage Range	-10V…10V
Number of DA Channels	32
AD Resolution	14 bit
AD Conversion Time	1.1 μs
AD Output Voltage Range	-10V…10V
Number of AD Channels	32
Encoder signal type	Digital
Position Counter Size	24 bits
Encoder Sampling Frequency	1.25 MHz
Number of Encoder Channels	15
Digital I/O Signal Type	0…5V TTL
Number of Digital I/O Channels	96

Table 4.2 – Hardware Specification

4.4.4 Autofocusing

Concept of autofocusing system is depicted in Figure 4.9. When laser beam (D) is focused with lens assembly (A) it is typically most concentrated and has the smallest waist diameter at the focal point of the lens. If the laser beam is assumed to have Gaussian beam profile, then due to the lens aberrations, the beam is at the focus over a distance called confocal parameter (B), and not in a single point. For the purpose of autofocusing, it is necessary to find the distance between the lens surface and the workpiece such that the workpiece is positioned within the confocal parameter, and then to keep this distance constant despite of surface variations on the workpiece.

In this work, a method for searching and preserving the location of focal point of the laser beam, in an automated fashion, is presented. As a measurement device, a 2D position sensitive detector (PSD) is used (C). PSDs are semiconductor optoelectronic devices used to determine lateral position of incident light. Typically, these devices combine position detection performance of CCD device and light irradiance measurement performance of PIN photodiodes.

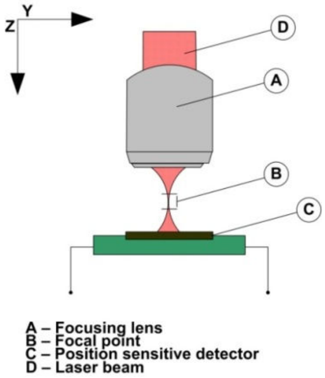


Figure 4.9 – Autofocusing system

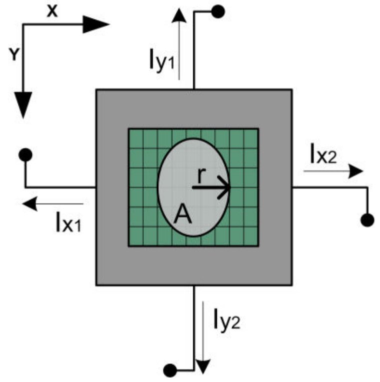


Figure 4.10 – Position sensitive detector

Photodiodes have linear responsively curve and consequently, for certain value range of incident power, the output photocurrent is linear and does not change with respect to varying size of incident light beam. However, photodiodes have a linearity limit on incident light power and can saturate if higher values are involved. If the photodiode is saturated it naturally becomes nonlinear due to high intensity of incident photons. When the device is operated in the nonlinear region of the responsivity curve, generated photocurrent becomes directly proportional to the incident beam size. If generated photocurrent density (A/mm^2) is considered to be a function of incident power distribution, total photocurrent generated can be formulated as the integral over area A shown in Figure 4.10.

$$I_{tot} = 2\pi \int_0^r J(\varphi) r dr \tag{4.10}$$

where $J(\varphi)$ is generated photocurrent density when light with optical power distribution φ is incident on photodiodes surface. For the case of typical Gaussian beam, power distribution can be defined as standard Gaussian distribution with zero mean:

$$\varphi = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-r}{2\sigma^2}} \tag{4.11}$$

where σ^2 is variance of the distribution and r is the radius of incidentlaser beam.

Total generated photocurrent is directly proportional to the incident beam radius r. This fact is taken as the starting point in the design of the autofocusing mechanism. Minimum value of the I_{tot} will be produced by the minimum radius of the beam. Advantage of this fact is that even without having exact knowledge of the photodiodes behavior in the nonlinear region of the responsivity curve or without any offline measurement, the light spot could be minimized, thus autofocusing done. Conceptual configuration of position sensitive detector is depicted in the Figure 4.10.

Figure 4.11. shows the measurement of photocurrent when the photodiode is translated along the optical axis of the incident laser beam. This way photocurrent values for different beam sizes can be recorded. Measurement of the generated photocurrent is done on two-dimensional position sensitive detector, DL16-7PCBA3 from Pacific Silicon Sensor, INC, laser used in measurement is low power 5mW laser whose wavelength is 640nm. Point F or some vicinity of it is the point of interest for autofocusing purposes.

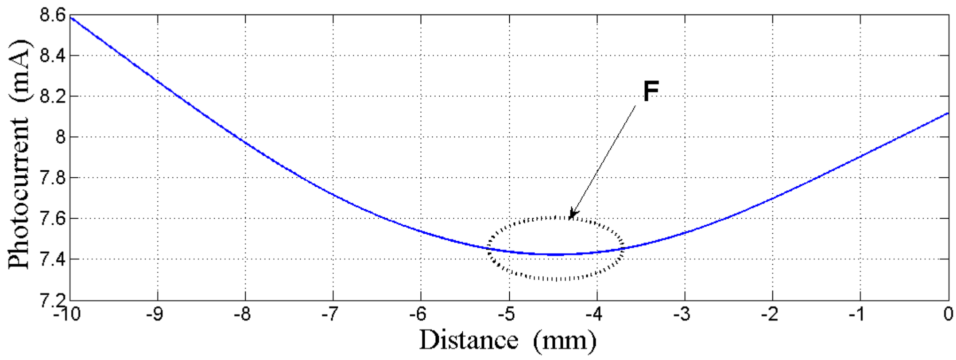


Figure 4.11. - Measurement of photocurrent vs. Distance

Adaptation of the sliding mode optimization algorithm can be done in order to arrange the motion of the system in such a way that output current reaches the minimum value and stays in that point or in some vicinity of that point regardless of surface changes on specimen. Sliding mode optimization algorithm, presented in [40,41], describes the method of finding minimum point of the function by first calculating the gradient of that function and then arranging the motion of the system towards the minimum point. Formulation follows that, if given output function $y = f(x)$ is assumed differentiable and its derivative $f'(x)\dot{x} \neq 0$ everywhere but in the point where $y = min(y)$, then the optimization algorithm can be described in the following manner:

$$\dot{x} = u$$
$$u = u_0 sign(\sigma_1, \sigma_2)$$
$$\sigma_1 = \varepsilon, \sigma_2 = \varepsilon + \delta$$
$$\varepsilon = g - y$$
$$\dot{g} = \rho - M\vartheta(\sigma_1, \sigma_2) \tag{4.12}$$

where u is the control input to the plant defined by state coordinate x, u_0 is positive switching gain, σ_1 and σ_2 are switching surfaces, ε is error defined as the difference between optimization reference g and measured output y. M and ρ are positive constants. Function ϑ is implemented as three-level relay element with hysteresis regions to avoid very high switching frequency [40].

Block diagram of the controller is given in Figure 4.12. Controller forces error ε to region defined and bounded by switching surfaces σ_1, σ_2 and parameter M. Once the value of error is inside this region the controller starts to minimize the output function y by modifying reference to the system. Minimization process is guided by the negative term - ρ. Once minimum point is reached controller starts to oscillate between upper and lower limit the relay function in order to keep output in a region near minimum point.

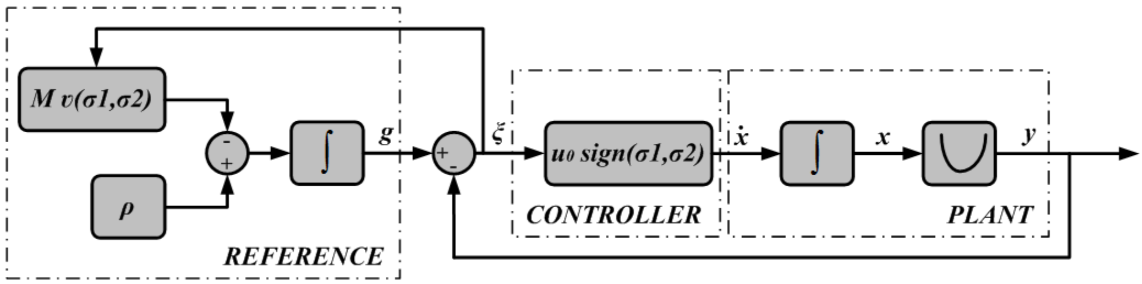


Figure 4.12 - Sliding mode optimization controller

4.5 Laser System

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 shown in the Figure 4.13. The technical specifications of the laser system are given in Table 4.3. The laser can be used for a variety of microprocessing operations such as scribing, ablation, Si processing, resistor trimming, Solar Cell processing, thin film cutting and marking. The red ENERGY™ G3 fiber laser platform uses SPI's Pulse Tune technology that offers flexible control over pulse width and peak power. This technology enables high repetition rates while maintaining peak power threshold. The laser beam is high quality beam with quality factor $M^2 < 2$. Fiber laser is easily maintained since it does not require replacement of parts.

Because of its lightweight (6 kg) and small volume (0.00537m^3) the laser module gives freedom to designer for optimum space utilization and flexibility with overall laser micromachining system design. The beam delivery optic supplied with laser has built in safety features and is resistant to back reflections. In some applications on highly reflective materials the interruption in operation caused by a core coupled back reflection is not desirable. The Isolator uses a Faraday rotator to eliminate all core coupled back reflections. The isolator can be attached to the beam delivery optic of lasers to prevent back reflected power perturbing the laser when working with reflective materials.

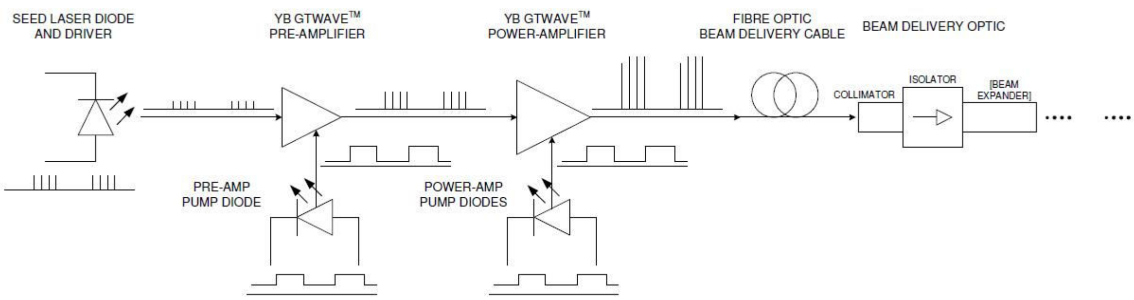


Figure 4.13. – SPI laser system (above) and schematic of pulsed operation (below)

Parameter	***Value***
Peak Emission Wavelength	1062±3 nm
Average Power	20 W
Peak Power	12 kW
Mode of Operation	Pulsed
Minimum Pulse energy	0.8 mJ
Beam Diameter	1-10mm with BET
M^2	1.6-2
Pulse repetition range	25-500 KHz
Output Power Stability	5.00%
Laser Module Dimensions	352 x 198.2 x 77mm
Laser module weight	6 kg
Polarization State	Random
Humidity	5 – 95% RH

Table 4.3. – Laser Characteristics

4.6 Beam delivery optics

The beam delivery optics is necessary in order to focus the laser beam to a small beam waist diameter and in turn increase the energy density of the laser beam. The laser micromachining system features Haas LTI laser micromachining fine cutting optics head shown in the Figure 4.14. (left). This head in particular was selected due to its compatibility with the SPI's fiber laser. Optics head incorporated with laser, illumination and vision system is sketched in Figure 4.14. (right). Optics head contains 2 beam splitters (BS) in order to incorporate the illumination light and on-axis camera (CCD) vision into the same path as laser light. The laser head focusing unit (FL) consists of set of three diffraction limited focusing lenses (triplet) with the focal distance of 50*mm*. Beam expander is mounted between the laser output port and the laser head input port. The function of this component is discussed earlier in the Chapter 3. Approximated final waist diameter of the laser beam is 10.8μm and depth of focus is around 54μm.

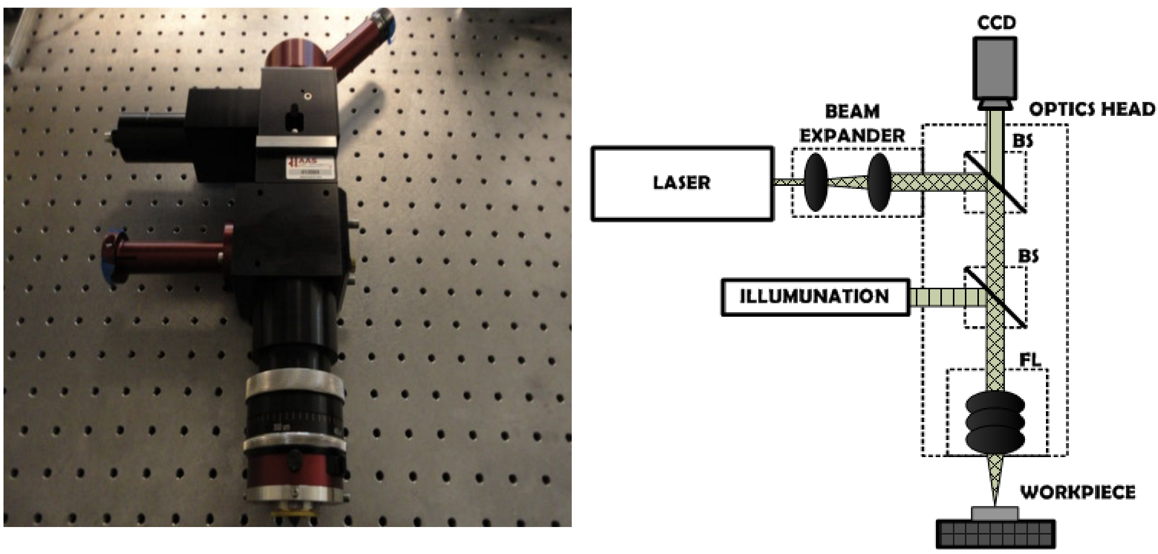


Figure 4.14. – Laser micromachining head (left) and sketch of optical system (right)

4.7 Software and MMI

Software for laser micromachining system was developed as a part of first version of framework for development of control software for complex mechatronics systems [X]. Our aim was develop the control system as structured as possible and ensure reusability of the developed functions in diversified mechatronics projects. The framework closely reflects the structural elements of a general mechatronics system. Software framework includes:

- *Realtime Development Module* - Realtime development module consists of a control library, interface functions and auxiliary functions to set up a hard realtime control system.
- *Realtime Interfacing Module* - Once a Realtime system has been established, it inevitably has the need to communicate with the outside world. For this purpose a realtime interfacing module is developed.
- *Hardware Module* - The hardware module contains hardware functions written in VHDL to create hardware control blocks running on an FPGA.
- *Graphical User Interface Module* - This module allows design of different GUI functions to easy the operation of a mechatronics system.
- *Control Library* - This section describes the control library that is composed of the different algorithms to provide precise motion control.
    - Position Control Functions
    - Velocity Control Functions
    - Acceleration Control Functions
    - Observers
    - Estimators
    - *Hardware Functions* - This section describes the hardware functions that have been created for the system. The hardware functions are coded with VHDL, and are programmed to an FPGA.
- Graphical User Interface - This section describes the graphical user interface of the framework.

The proposed design methodology combines initially a top down and bottom up methodology which is applied simultaneously in a methodological manner, where the top down approach is used to well define the necessities of the systems and the bottom up approach is used to model the different hardware and information components of the system in a semi object oriented manner. Then the two approaches meet in the middle in a common mechatronics language. The design iteration is performed until the completion of the tasks. The whole approach relies heavily on a well structured form of layering to facilitate the separation the different problems relating to the different engineering fields of the global task. In this methodology each layer possesses its own difficulties and necessitates its own auxiliary functions. Common libraries forming a framework greatly improve the development time and development ease of the mechatronics system. These libraries can range from ones containing control functions for the motion control layer to database connections and data-mining functions.

4.7.1 Man machine interface (MMI)

The picture of the user interface is shown in the Figure 4.15. Sections of the interface are numerically labeled and represent following:

1. Menu Bar
2. Laser Parameter Selection Menu: selection can be made among the pre-programmed laser waveforms, laser modes, laser states and power options
3. Laser Signals On/Off buttons: Buttons used for controlling of various laser signals responsible for releasing of the light beam.
4. Laser power, Laser temperature and parameters monitoring indicators.
5. Laser Ready and Laser error light indicators
6. Motion platform manual control button set
7. Platform Indicators
8. Miscellaneous Functions Buttons
9. Task List Control and Visualization Buttons
10. Screen area reserved for showing of micromachining pattern
11. Section for setting of parameters of preprogrammed pattern and shapes

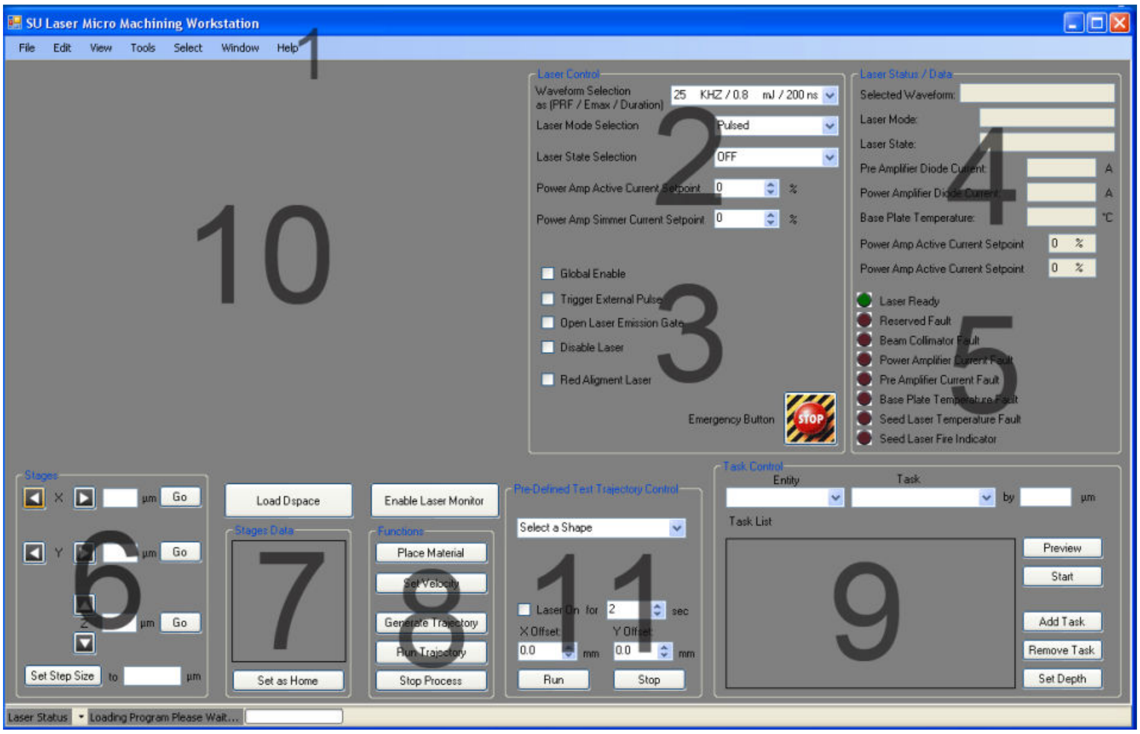


Figure 4.15. – Laser micromachining system Graphical User Interface

4.7.1.1 Display Modules

The description of the graphics display module and laser state / data display modules is given in details. The graphical user interface was programmed using C# programming language.

4.7.1.1.1 Graphics Display Module

User selects and opens the technical drawing file containing feature or pattern to be micromachined. The file is then processed and it is shown in the area numbered by (10) in the Figure 4.15. In order for this task to be accomplished graphics module is running in the background. This module is programmed to extract the display information out of technical drawing file and display it using canvas class in order for user to see it. In order to demonstrate this procedure, the "sample1.dxf" technical drawing file is opened and displayed in the Figure 4.16. After the file is opened and displayed on the main screen, user can modify technical drawing by clicking on the displayed pattern.

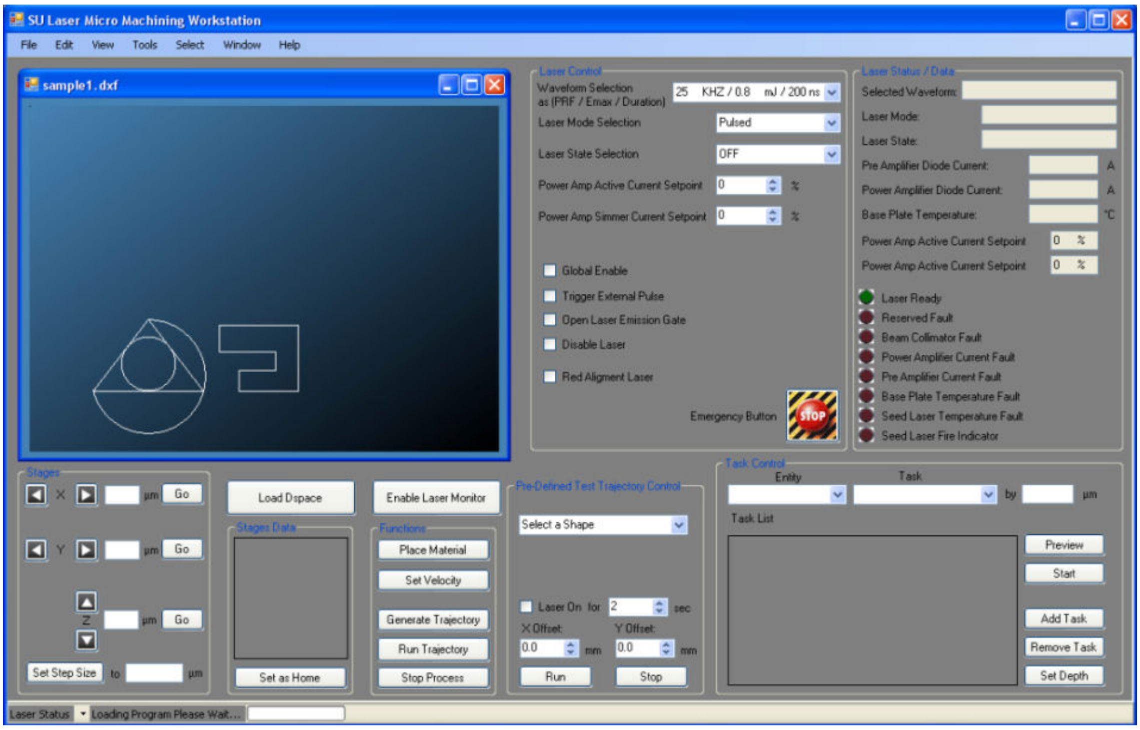


Figure 4.16. – Example accomplished by Graphics Display Module

4.7.1.1.2 Laser state / data display module

It is necessary to display the lasers state and data during laser micromachining process. This module displays the current status of laser preamplifier and power amplifier stages, laser amplifier temperature, laser mode, energy waveform and any occurring errors. The display of these data is crucial for the successful operation of the system. The laser state/data display module is responsible for communication with laser and displaying the communication contents to the user. It allows the user to monitor laser condition directly from the main menu and take any preventive actions if necessary. The graphical user interface side of this module is shown in the Figure 4.17.

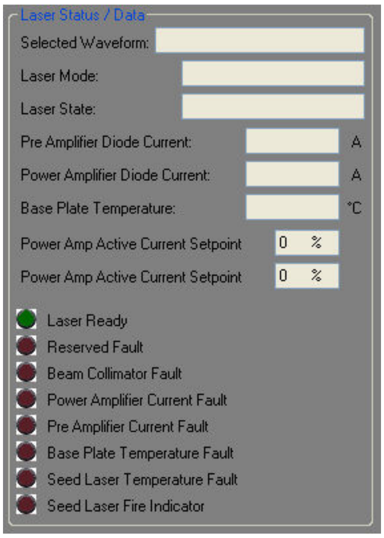


Figure 4.17. – Laser state/data display module interface

4.7.1.2 Input/Setting Modules

In this section the input/setting modules are presented. These modules include motion platform module, laser settings module and graphics input module.

4.7.1.2.1 Motion Platform Module

This module is responsible for the generation of the motion references, namely position, velocity and acceleration. The execution of motion planning algorithm described in the section 4.4.2.2 is done by this module. Besides automatic generation of motion references based on data obtained from the graphics input module, this module allows the manual position input directly from the user. The interface for manual position input is shown in the Figure 4.18.

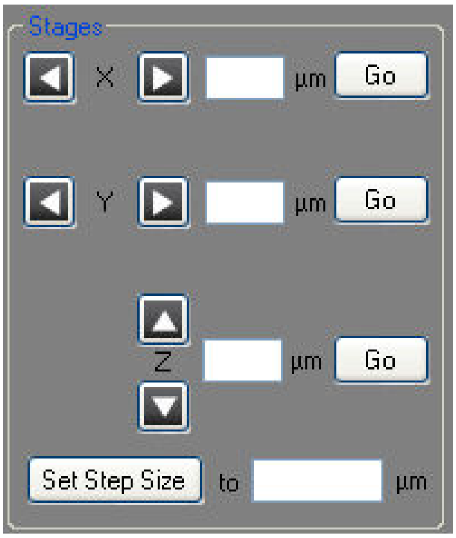


Figure 4.18. Manual position input buttons

4.7.1.2.2 Laser Settings Module

It is necessary to select proper laser settings in order to laser micromachine the specific type of material. Pulse repetition rate, per pulse energy and pulse width are combined into the setting called the waveform. This module contains 29 different types of preprogrammed waveforms supplied by the laser manufacturer. From the moment when the internally generated pulse is produced until the moment when it comes from the output of the laser, it is necessary to adjust some additional laser settings. This module allows both the waveform selection and those setting arrangements. The graphical interface of this module is shown in the Figure 4.19.

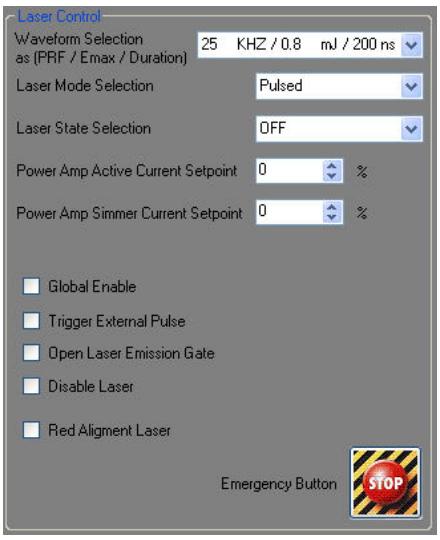


Figure 4.19. – Laser Setting Module

4.7.1.2.3 Graphics Input Module

This module is responsible for importing of the technical drawing file previously saved in .dxf format. The detailed information about this type of file is presented in Section 4.4.2.1. This module imports the .dxf file, extracts the coordinate description of the part/pattern to be machined, performs the data interpolation and sends the interpolated data to the motion platform module. The graphical interface abilities of this module are presented in the next three figures.

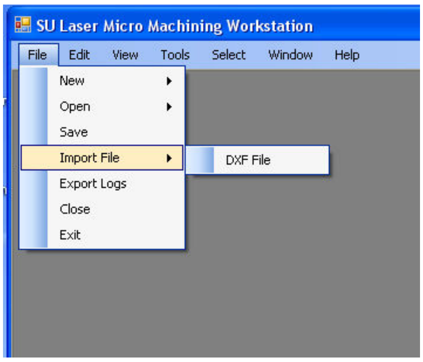


Figure 4.20. – Import of file from the menu bar

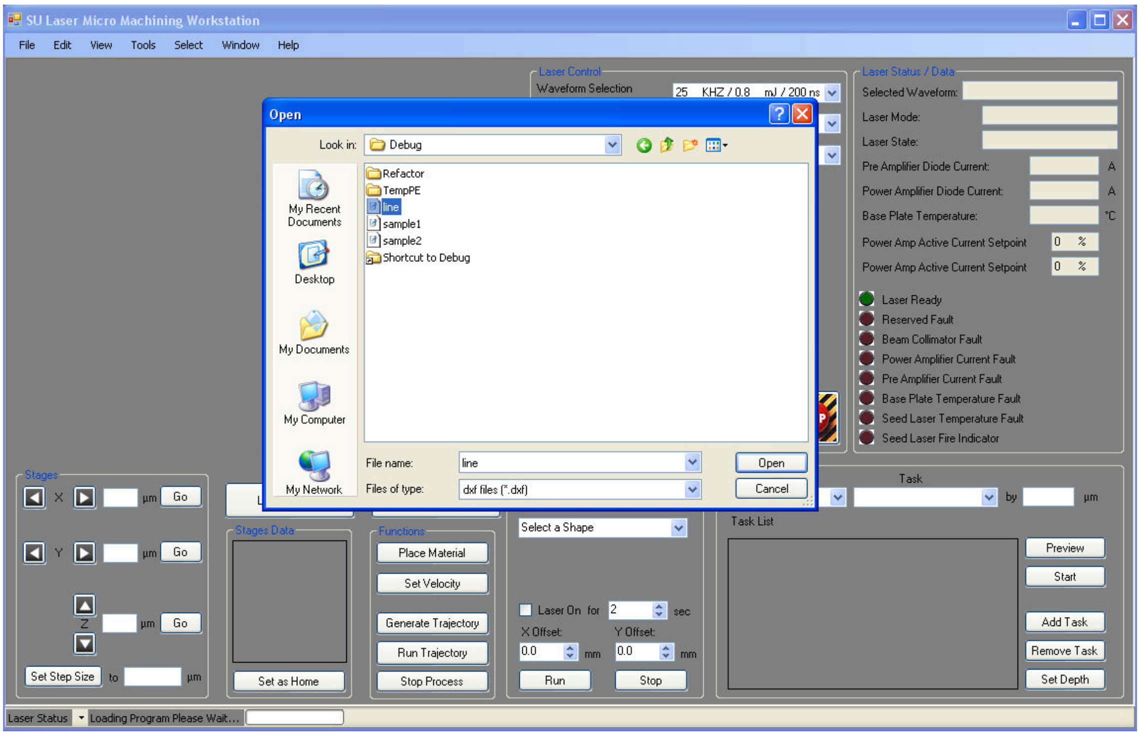


Figure 4.21. – Selection of file

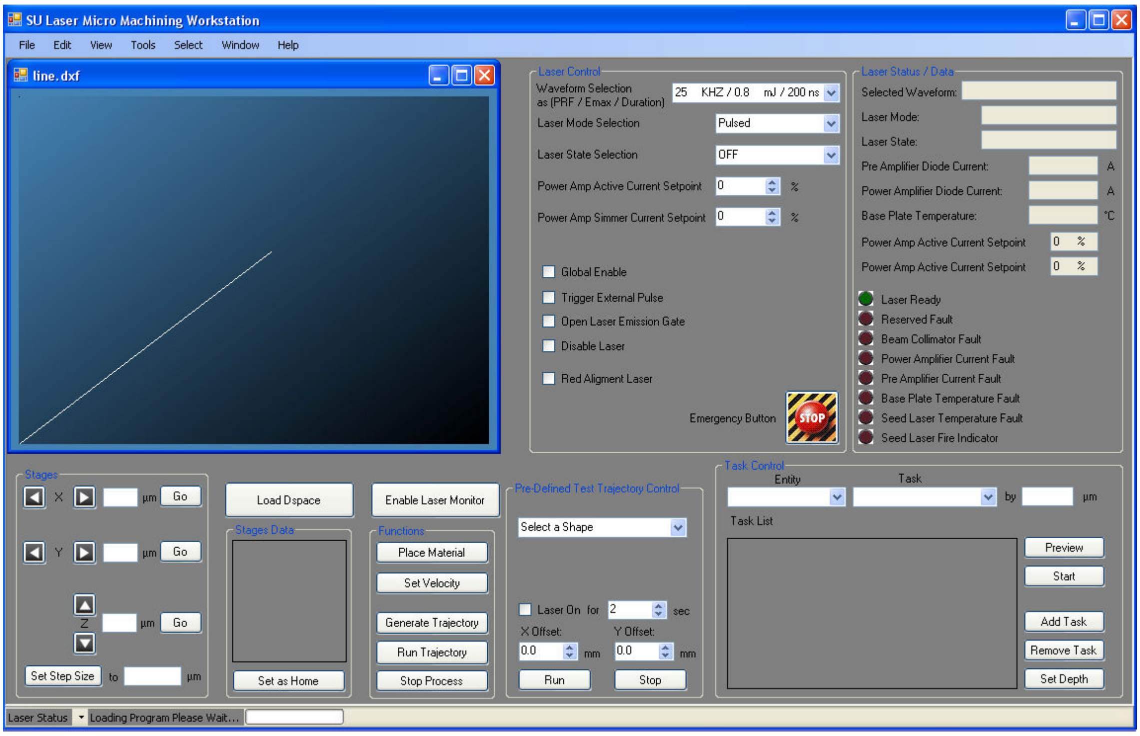


Figure 4.22. – Screenshot after the .dxf file import

5 SYSTEM IMPLEMENTATION

5.1 Introduction

In order to verify the proper mechanical design of planar x-y positioning stage and proposed control algorithm scheme series of experiments were done on the motion platform. The proposed modified sliding mode optimization algorithm application to a laser autofocusing system is experimentally validated. Finally, in order to show the proper operation of the entire laser micromachining system and to verify that the design system meets the requirement of laser micromachining process the series of laser micromachining experiments were made, including the ablation, scribing and drilling hole in various materials. The experimental settings for these results are described in detail in the subsequent sections.

5.2 Planar x-y Positioning Stage Experiments

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 system purposes, two experiments for circular references of different diameters were preformed on the designed x-y motion stage. Experiments were 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. First experiment is done for the circle reference whose radius is 100µm. The results for the trajectory tracking are shown in the Figure 5.1. Error in the tracking is treated as the difference between the reference time varying trajectory and actual trajectory (position information obtained from optical encoders). Errors for each axis are shown in Figure 5.2. and Figure 5.3. Errors are given in micrometers and it is observed that the errors are usually lower than 0.5µm with peak points of 0.8µm at some instances throughout the motion.

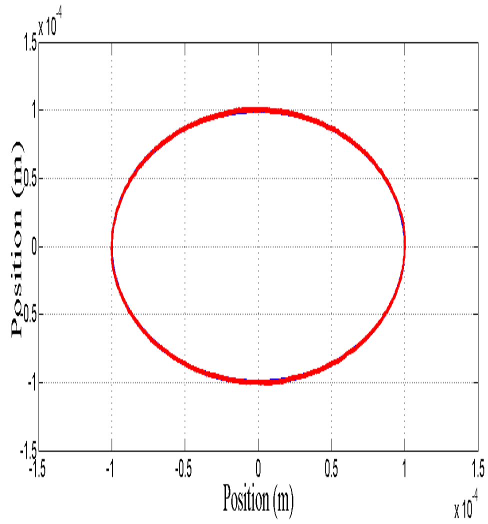


Figure 5.1. - Trajectory tracking for circular reference of 100µm radius

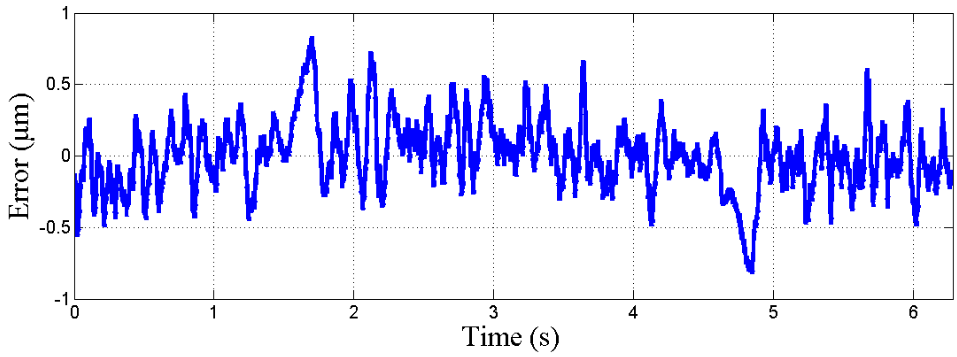


Figure 5.2. – Error in trajectory tracking for x axis

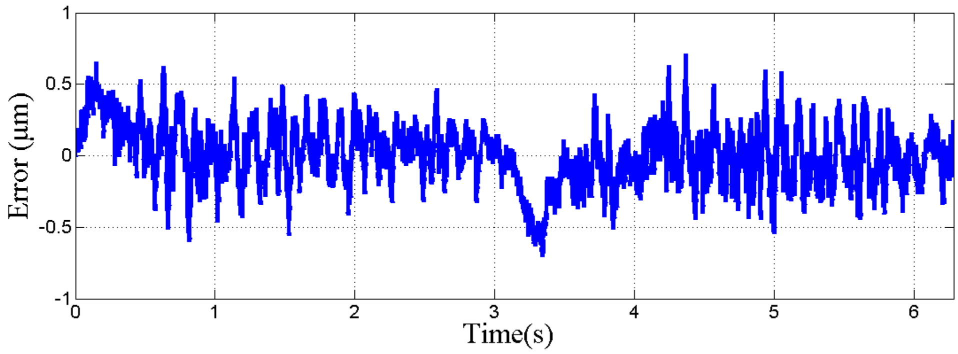


Figure 5.3. – Error in trajectory tracking for y axis

Second experiment is done for the circular reference with the radius of 30µm. The results of trajectory tracking are shown in the Figure 5.4. and errors in tracking for corresponding axes are shown in Figure 5.5. and Figure 5.6. It can be observed that the value of errors for the motion of both axes is not significantly decreased although the circular reference in the second experiment has much smaller radius than the one in the first experiment. The control gain parameters for the stage were tuned to give the best performance in the trajectory tracking control. Gains were increased even further; however the value of error did not decrease.

Even small, the errors for both experiments 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 exceptionally small geometrical features such as circular references of 30µm radius. Even though errors in reference tracking are reaching up to 0.5µm for 30µm radius references, this performance is acceptable for the use in the described laser micromachining system since the approximated laser beam waist diameter is around 10.8µm. 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 a laser micromachining process quality.

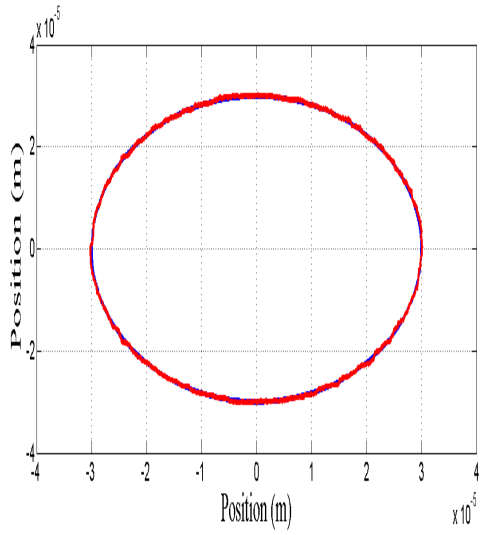


Figure 5.4. - Trajectory tracking for circular reference of 30µm radius

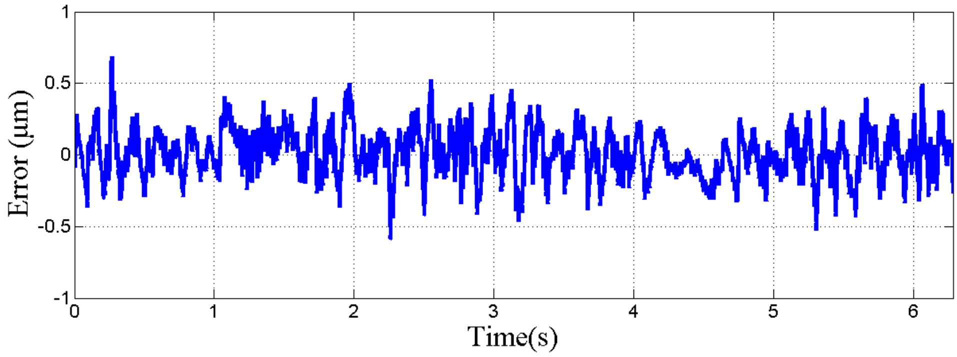


Figure 5.5. – Error in trajectory tracking for x axis

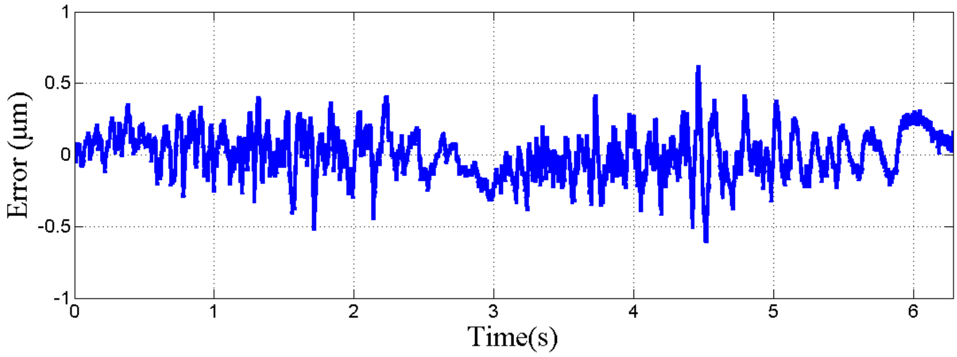
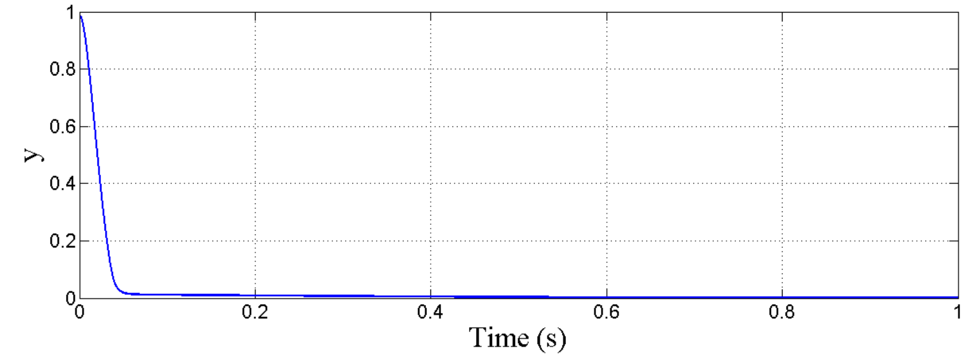


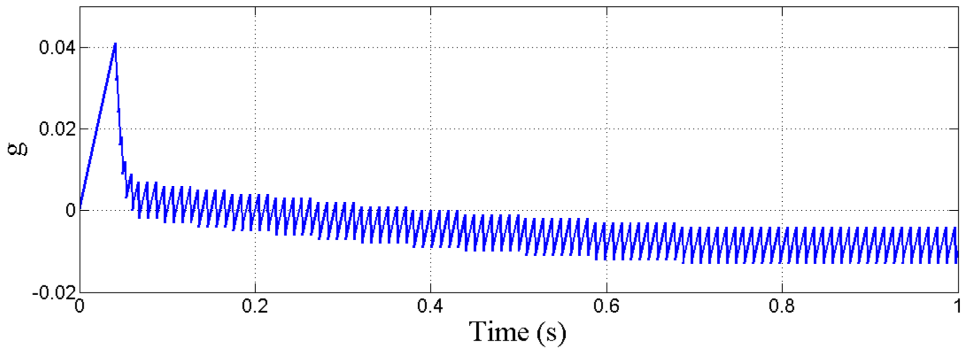
Figure 5.6. – Error in trajectory tracking for y axis

5.3 Autofocusing system simulation and experimental results

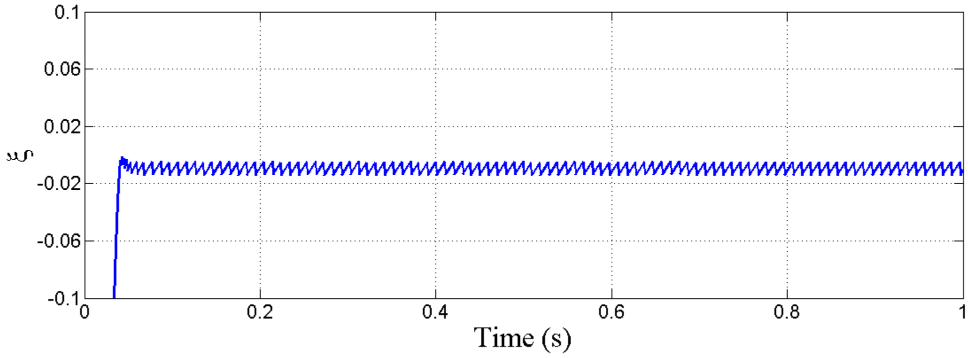
The sliding mode based minimization algorithm is simulated and results are shown in the Figure 5.7. Motion of the system is arranged such that error, given in Figure 5.7.-c, between the reference, shown in the Figure 5.7.-b, and output of the system reaches the region defined by the switching surfaces. Once the error value reaches this region, the minimization process starts, this can be observed in the Figure 5.7-b between 0.05s and 0.7s. Once the minimum point is reached, output stays in that point. Rate by which output reaches the minimum condition is dictated by the constant ρ. Steady state oscillations in the output value are slow and can be further decreased depending on the technical requirements and design constraints. Steady state error takes the value of parameter δ. Steady state error could be decreased by decreasing this parameter, however this could bring instability to the system. The amplitude of oscillations in the error depends on the hysteresis value of relay.



(a) Simulated Output



(b) Simulated Reference



(c) Error

Figure 5.7. – Simulation results for autofocusing system

In order to verify the usefulness of the sliding mode optimization algorithm for autofocusing purposes, experiments were conducted on an experimental system consisting of high precision linear stage, position sensitive detector and pilot laser light beam. Precision linear stage is PI's M-111.1DG DC-motor actuated Micro Translation Stage with motion resolution of 7nm and travel range of 15mm. Position sensitive detector used is DL16-7PCBA3 from Pacific Silicon Sensor, INC. It is a 4mm x 4mm dual axis position sensing diode on a PCB with sum and difference amplifiers. Outputs are bipolar voltage analogs of the X and Y position of the light spot centroid, as well as the total photocurrent generated in X direction and the total photocurrent generated in Y direction. These sum outputs were used to measure total photocurrent generated by incident light. Pilot laser used is IMM's low power laser with optical output power of 5mW. Wavelength of the laser is 640nm. Dspace DS1005 is used as controller running at 10 KHz sampling frequency. Output of the PSD is converted with a 16-bit AD converter and passed through a digital low pass filter with cut-off frequency of 10Hz to obtain smooth signal. Experimental setup is shown in Figure 5.8. PSD is mounted on the translational stage in order to translate the photodiode along the optical axis of the laser lens.

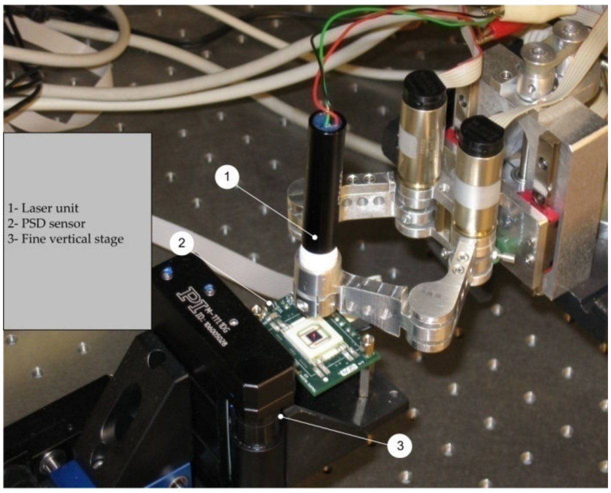
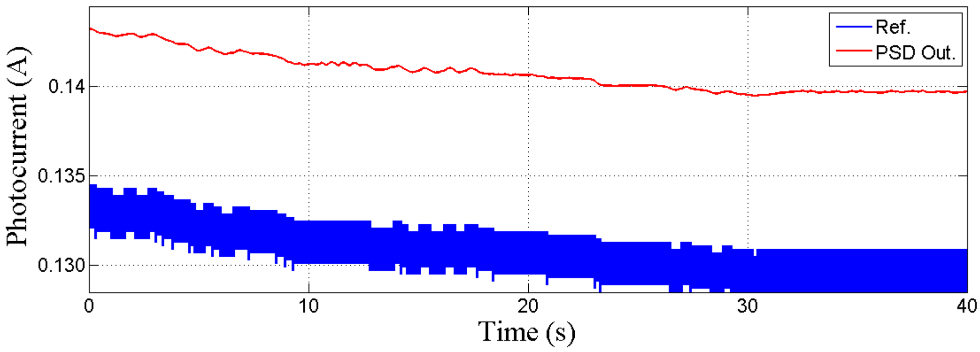
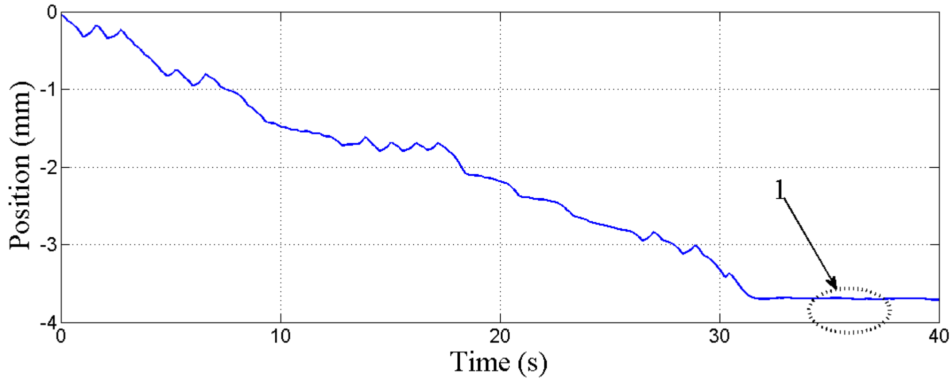


Figure 5.8. – Experimental setup

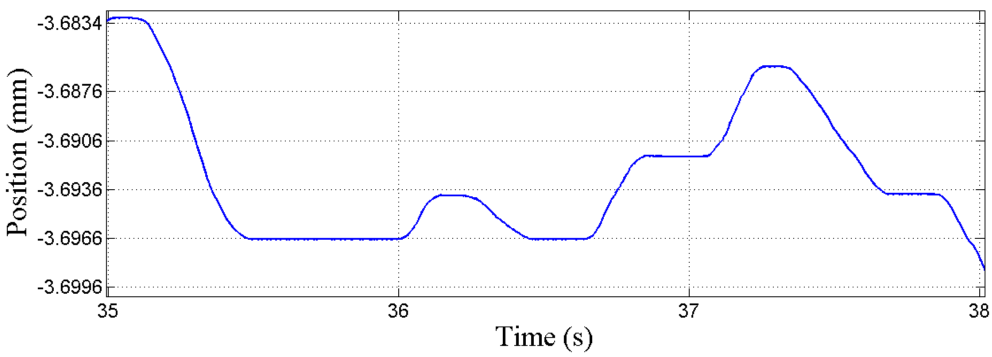
First experiment is conducted such that translational stage is initially positioned away from the focal spot of the lens. System starts to move in order to minimize output and finally reaches the focal point of the lens. It must be noted that PSD is very prone to noise contamination because no reversed biased voltage is applied to the terminals of the photodiode. Besides using very low cutoff frequency digital lowpass filter, signal levels of the output are kept low to avoid any unnecessary oscillations. Plots of the reference to the system and output of the system is shown in Figure 5.9. The theoretical assumptions are verified and convergence of output to the minimum point is observed



(a) Reference and Output vs. Time



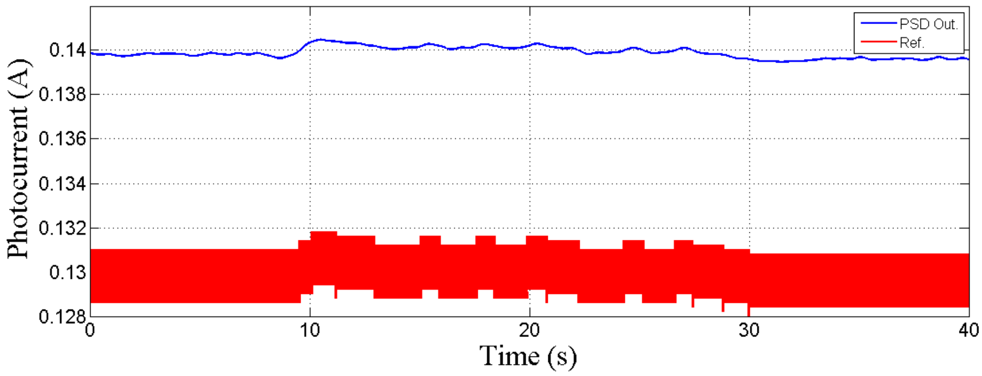
(b) Encoder readout



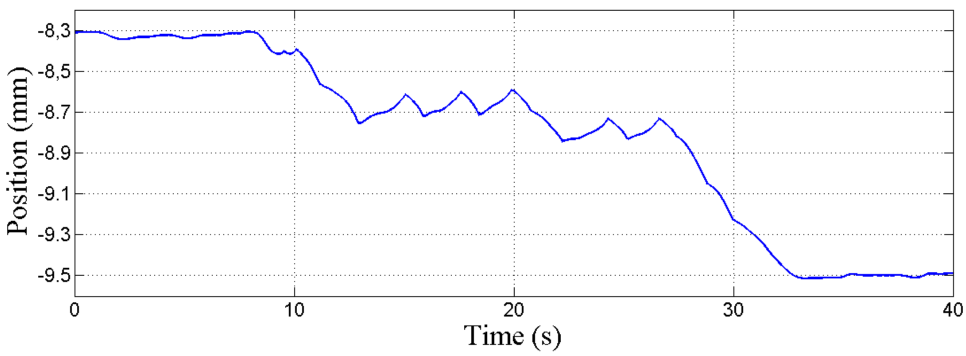
(c) 1 magnified

Figure 5.9. – Autofocusing system experimental results 1

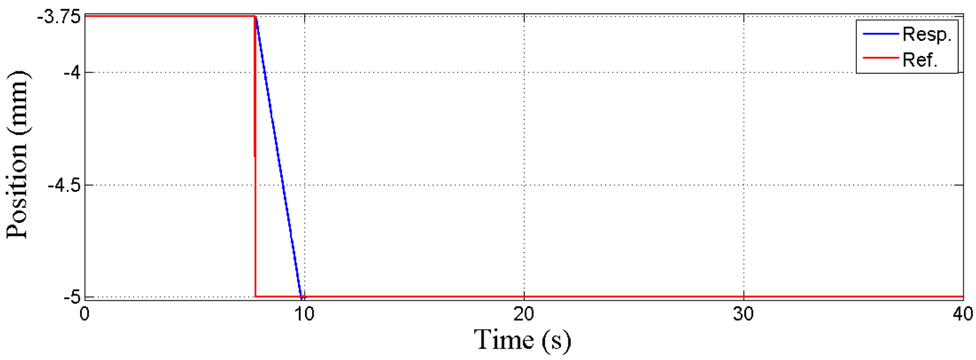
Second experiment demonstrates system response to the surface variation. Surface variation is simulated by translating pilot laser unit vertically, along the optical axis of the lens. Laser is attached on the separately controlled DC motor with optical encoder as a measurement unit. Results of this experiment are given in the Figure 5.10. At the beginning of the experiment the distance between the surface of the lens and surface of the PSD is equal to the focal length of the lens and light is focused. Laser is translated along the optical axis by the arbitrary distance of 1.25mm, Figure 5.10-c. Systems reference and photocurrent measurement is shown in the Figure 5.10-a. It is observed that after some time these values return back to the initial values, thus relative distance between the lens and PSD is kept constant. Encoder value of the translational stage is shown in the Figure 5.10-b, the difference between the initial and final value of encoder readout is 1.197mm. The absolute error between the two encoder values is 53µm.



(a) Reference and Output vs. Time



(b) Encoder readout



(c) Step response

Figure 5.10. – Autofocusing system experimental results 2

5.4 Laser micromachining experimental results

In order to demonstrate the operational and functional capabilities of the designed laser micromachining system, series of experiments were conducted, including precision marking of anodized aluminum, subsurface marking of glass, ablation of brass and drilling holes in brass material. Power/energy capabilities of laser are demonstrated as well. In the subsequent sections these experimental results are presented and evaluated upon.

5.4.1 Precision marking of colored anodized aluminum

Lasers are often used to mark anodized aluminum. The laser effectively removes the anodized aluminum giving a very high contrast and permanent mark. Colored or black anodized aluminum are the most common types marked by lasers. The interesting point about this type of laser marking is that either a dark or a light mark can be made dependant on the power of the laser used.

In order to demonstrate the motion platform capabilities and the generation of more complex geometry shapes, precision marking of coated anodized Aluminum alloy 6061 was done. The laser repetition rate was set to 25 KHz, the pulse width to 200nm and per-pulse energy to 8mJ. The laser was run at an average of 25% of its total average power, namely 5W. Obtained results are shown in the Figure 5.11., 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.

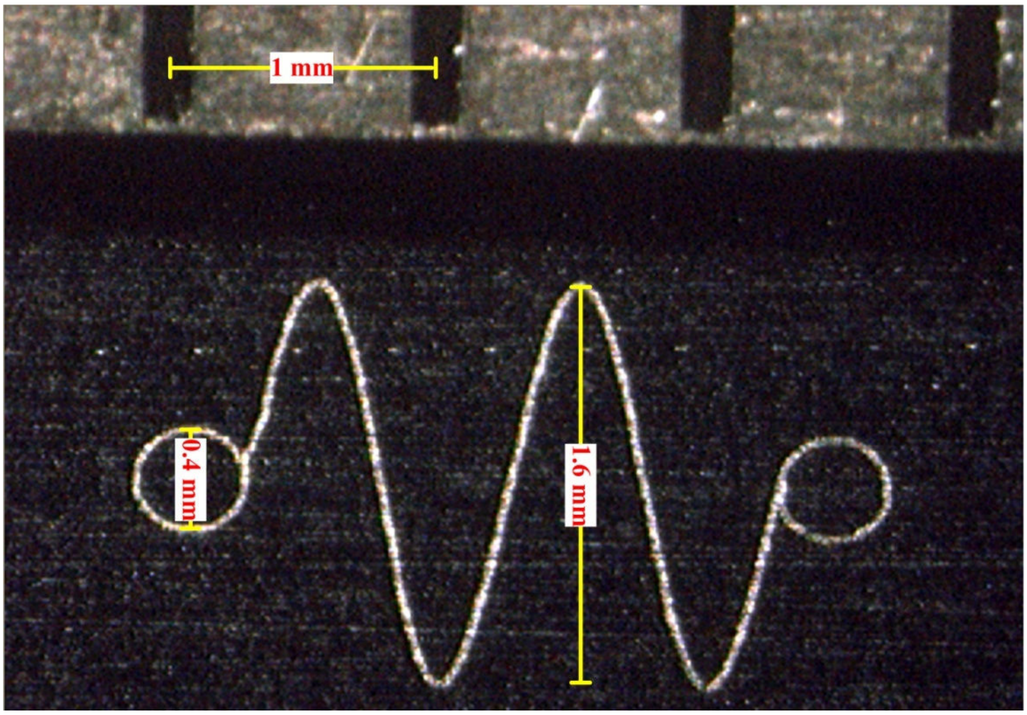


Figure 5.11 – Marking of coated anodized aluminum

5.4.2 Subsurface marking of glass

Subsurface marking is an application of interest to the decorative, medical packaging and other industries where identification information is critical and must be protected from duplication. Laser processing of glass presents tough challenges due to its brittle nature and poor heat transfer. The process of generating an internal mark inside the glass material causes the thermal fractures resulting in microcracks formation. For decorative applications, infrared (IR) wavelengths are most suitable because glass is transparent at these wavelengths unless the intensity is very high. In other words, with proper process adjustment, the melting of glass can be selectively initiated only at the focus point of the laser beam.

In this experiment the marking of microscopic slide glass is preformed. The slides are made about of fused quartz which is transparent to infrared wavelengths. The experimental results of subsurface marking of glass are shown in Figure 5.12. In the upper portion of Figure 5.12., in the area marked with “A” the crack due to the thermal stress can be observed. The lower portion of figure shows the magnified circular shape. The motion reference was circle with 1mm in diameter. The laser repetition rate was set to 25 KHz, the pulse width to 200nm and per-pulse energy to 8mJ. The laser was run at an average of 85% of its total power, namely 17W.

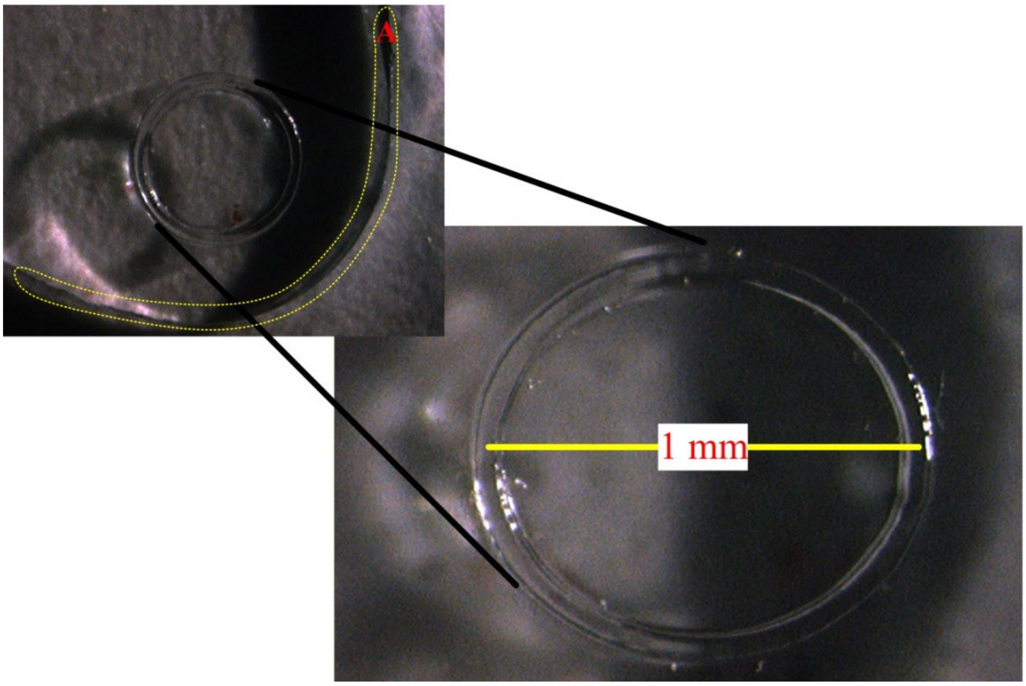


Figure 5.12 – Subsurface marking of glass

5.4.3 Drilling holes in brass

Lasers are usually used for drilling holes by removing circular disc from substrate. One of the most used methods for drilling holes is trepanning. Trepanning is the standard technique for large holes, e.g. 500 micron holes in turbine blades. The application of nanosecond pulses to trepanning can increase the quality of the hole. If the drilling of holes is done with low power lasers, the process takes a lot of time to complete.

Drilling of hole in brass material is preformed using trepanning method and results are shown in Figure 5.13. The motion reference was circle with diameter of 0.5mm. The laser repetition rate was set to 25 KHz, the pulse width to 200nm and per-pulse energy to 8mJ. The laser was run at an average of 100% of its total power, namely 20W. Brass thickness in this sample was 0.28mm. The total drilling time was 300 seconds.

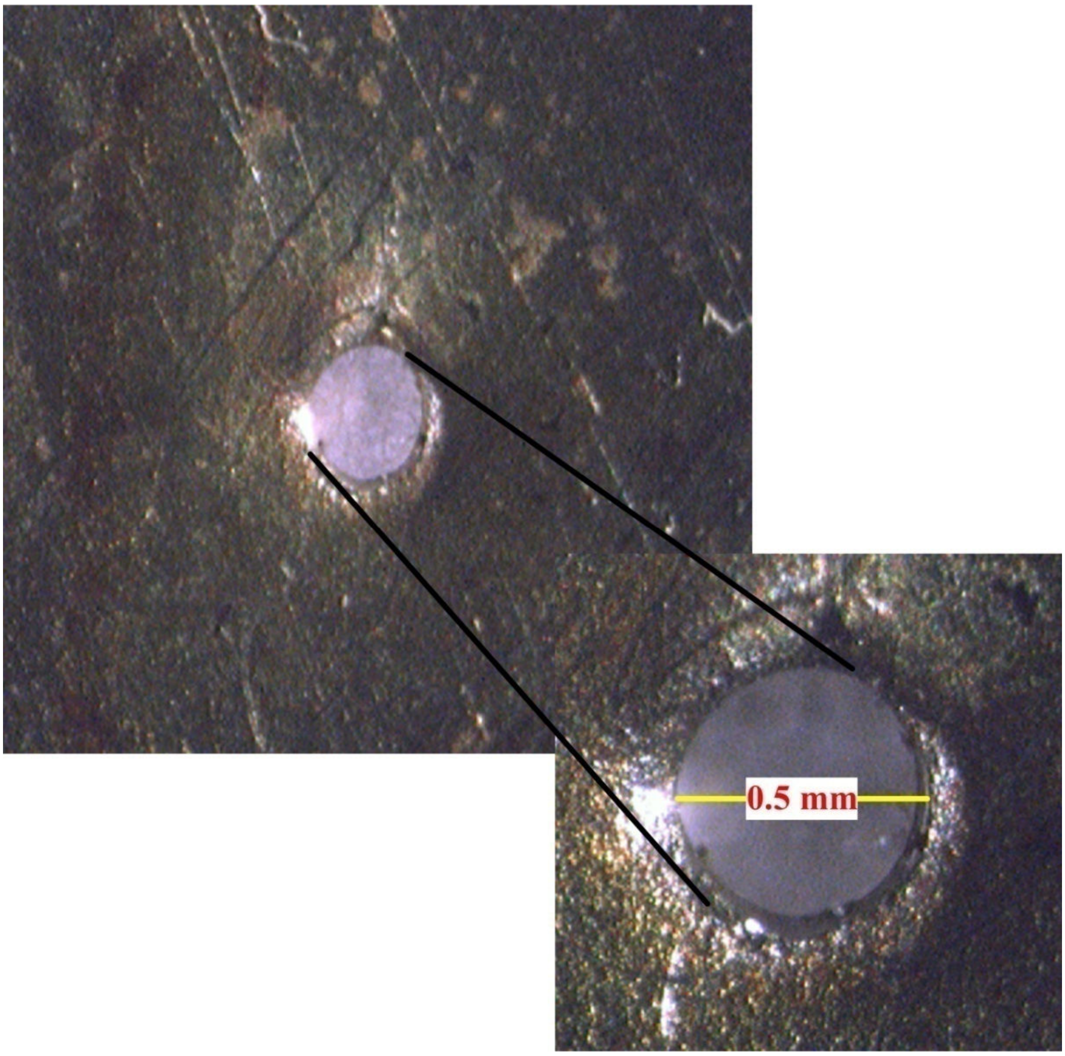


Figure 5.13 – Hole drilled in Brass

5.4.4 Micromachining of Brass

Material removal from brass sample is shown in the Figure 5.14. Series of circular channels were machined, starting with the largest with diameter of 1mm to the smallest with the diameter of 0.4mm. The channels were machined with multiple passes of laser beam on the material. The laser repetition rate was set to 25 KHz, the pulse width to 200nm and per-pulse energy to 8mJ. The laser was run at an average of 100% of its total power, namely 20W. The channel was created in total of 3 passes of laser beam on the material. The figure in the lower right corner is magnification of part of one of the channels, where the recast material and the depth of channel can be observed.

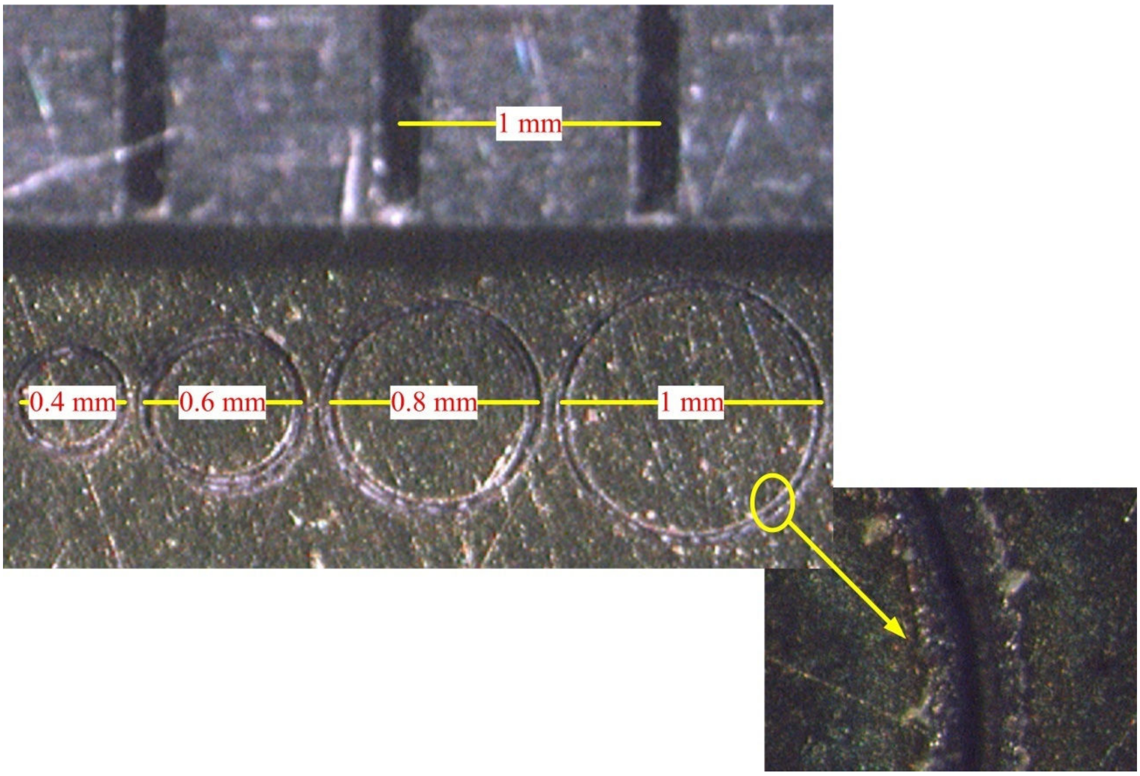


Figure 5.14 – Brass Machining

5.4.5 Laser power capabilities

In order to demonstrate the laser power capabilities two experiments were conducted. First one is done in coated anodized Aluminum alloy 6061. The laser repetition rate was set to 25 KHz, the pulse width to 200nm and per-pulse energy to 8mJ. In Figure 5.15. (top) the laser was run at an average of 20% of its total average power, namely 4W. In the bottom figure the laser was run at full power, 20W. The difference was observed primarily in the width of the mark. In the 4W case the colored layer on the anodized aluminum is removed and the brightness of the mark is low whereas in the 20W case the brightness in much higher.

Figure 5.16. shows the results of second experiment. This experiment is done in brass and in slightly different manner than the first one. Namely laser was set to 25 KHz, the pulse width to 200nm, per-pulse energy to 8mJ and total average power to 20W. The difference between the result at top and bottom of Figure 5.16. is in the total number of laser beam passes on the material, 5 for feature at top and 10 for feature at bottom of figure.

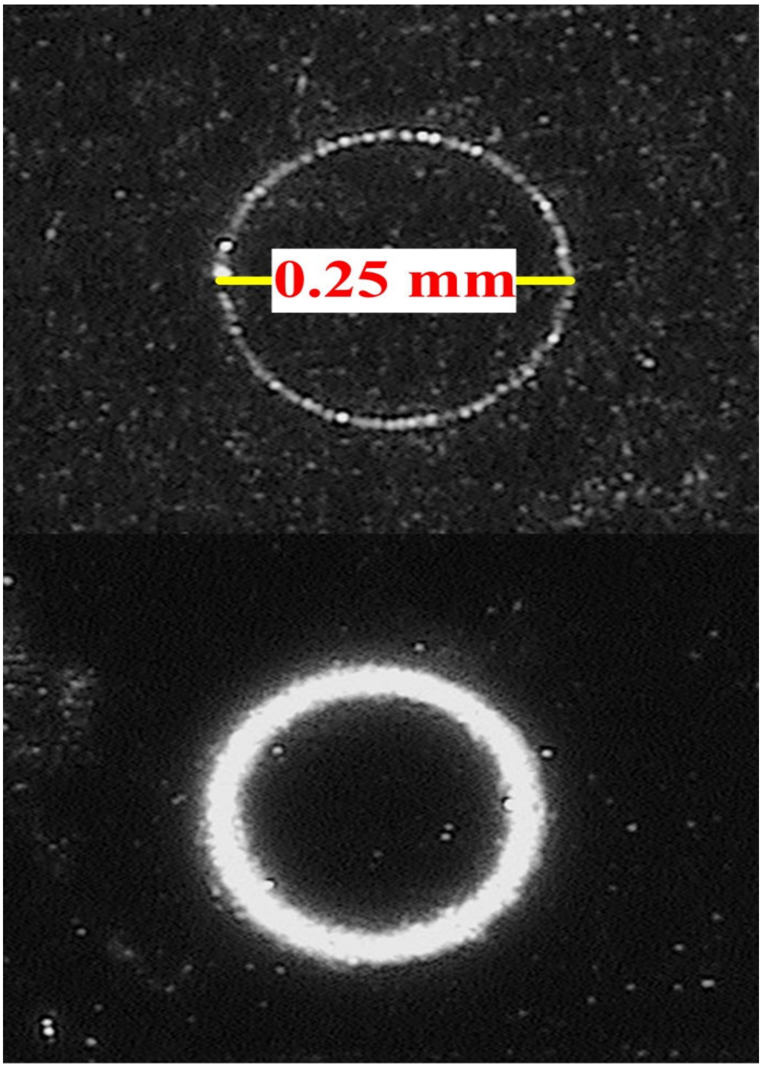


Figure 5.15 – Power experiment in anodized aluminum

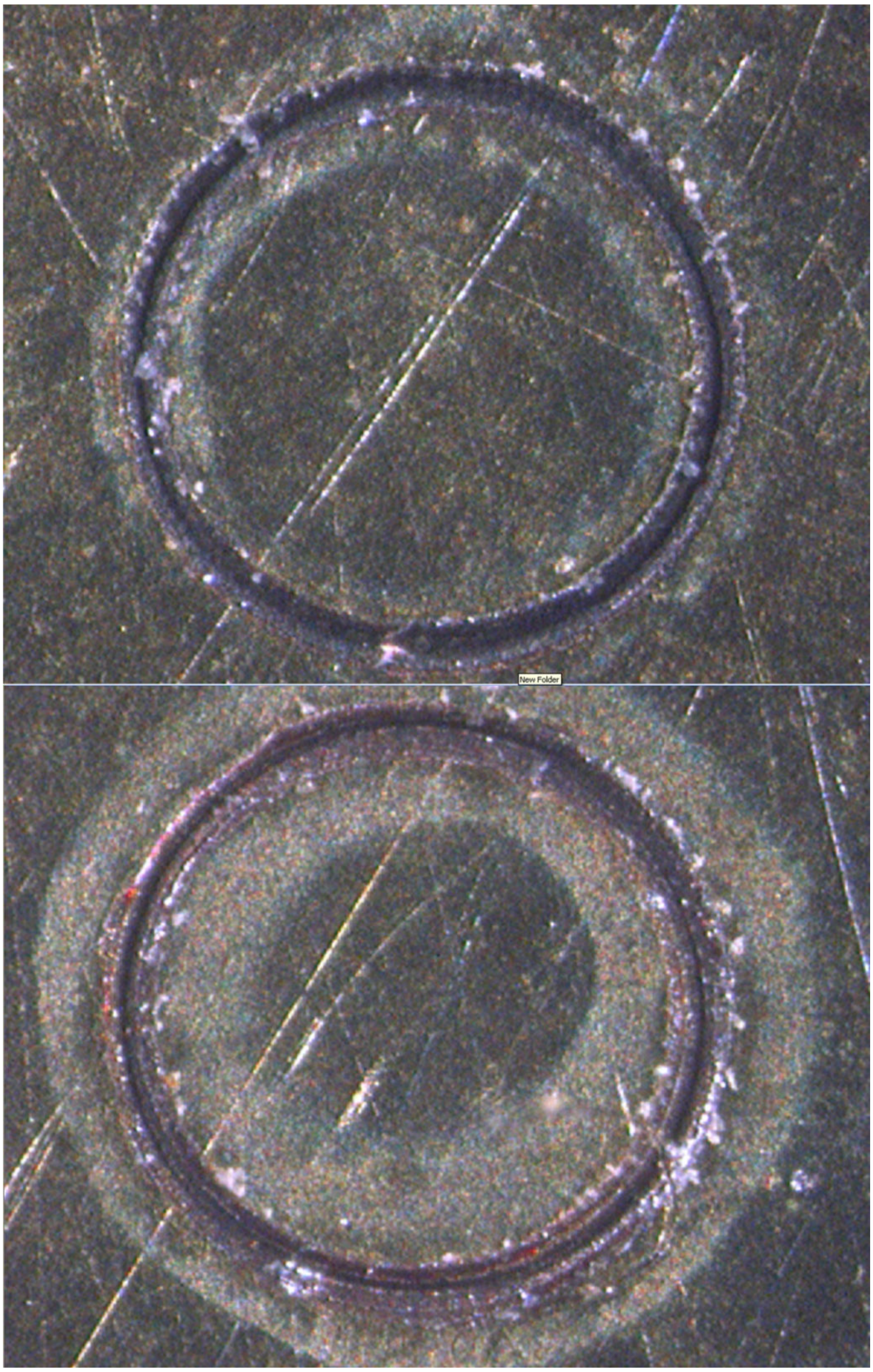


Figure 5.16 – Power experiment in brass

6 CONCLUSION AND FUTURE WORK

In this work, the design and realization of modular direct write laser micromachining workstation capable of performing micromachining operations such as microscribing, ablation, Si processing, resistor trimming, solar cells processing, thin film cutting, micromarking, etc. is presented. The design requirements for such system are explained in detail and implementation considering these requirements is demonstrated. Selected results of precision scribing, hole drilling and material ablation are presented as well.

Quality of laser micromachining process is mainly affected by three factors, laser, laser-material interaction and the design of the overall micromachining system. The work in this thesis mainly focused on the improving of the design of laser micromachining system in order to increase the quality of the process itself. The main emphasis was on the design of motion control system. In this light following were done:

- Mechanical design of the overall system is done with respect to the defined design requirements guarantying desired precision of motion. The overall system has four degrees-of-freedom.
- Precise positioning linear planar stage having resolution, accuracy and repeatability in the submicron region was designed. The experiments of position tracking were performed on this stage and the proper design was verified.
- Software together with man machine interface that allows both manual and automatic alteration of critical process parameters such as laser power, pulse repetition rate, pulse duration, etc. is designed

The system is currently controlled by the prototyping control hardware. In the future we plan to do the redesign of the control hardware by employing industrial (single board) PC in combination with the peripheral devices hardware cards. In addition the migration of the system is planned to be done to Linux operating system.

Another future aim is set concerning the research on the software structure design and development of the second version of software scheme for the control of complex mechatronic systems.

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