Mechanical Design of Optics Bench for UV-LED Based Liquid Chromatography Detector

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Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of

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Submitted to the Department of Mechanical Engineering on August 10, 2015 in partial fulfillment of the requirements for the Degree of Master of Engineering in Manufacturing.

ABSTRACT

The proposal for a new detector for liquid chromatography instruments that uses Ultraviolet Light Emitting Diodes (UV-LEDs) as the light source as opposed to currently used deuterium lamps required new design of the mechanical and structural components associated with it. The optics bench assembly is the heart of the detector system on which the detector optical components are mounted. The focus of this thesis is the mechanical design of the optics bench assembly of the UV-LED detector. The thesis first briefly describes the technology and operational theory of the new detector and then discusses the considerations when designing the optics bench. The thesis then presents a step by step methodology of mechanical design of the optics bench assembly. Based on functional requirements of the bench, the best suited material which minimizes vibration sensitivity, thermal gradient, distortion due to impact loading, and cost was selected. The optimal wall thickness of the optics bench was determined by analyzing the results of drop test and vibration analysis. Features to isolate the optics bench assembly from vibration, shock, dust and humidity are also discussed. Thermal analysis was carried out to find out the amount of thermal gradient produced in the optics bench assembly due to thermal heat sources. Based on the results of the thermal analysis, the design of a robust thermal management system is proposed. Guidelines for design for manufacturing, assembly and serviceability were considered at each step of the design process. On the basis of the design requirements and cost considerations, the best suited manufacturing process and surface coating was determined. In conclusion, this thesis offers a foundation and a starting point for the detailed mechanical design of optics bench assembly for UV-LED detector.

Thesis Supervisor: Dr. Jung-Hoon Chun
Title: Professor of Mechanical Engineering

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CHAPTER 1: INTRODUCTION

Liquid chromatography (LC) is a technique in analytical chemistry that is used to separate, identify and quantify each component in a mixture. The major components of the liquid chromatography systems are Sample Manager, Solvent Manager, Column Heater or Column Manager and Detector. In LC systems a pressurized liquid solvent containing the sample mixture is passed through a column filled with a solid adsorbent material. As the sample mixture is passed though the column, the components of the mixture separates out due to different flow rates as each constituent of the mixture interacts differently with the column absorbent. A detector is a device used to identify components of the mixture being eluted off the chromatography column by directly measuring the light absorbing or any other property of the column eluent. The current detector systems uses deuterium lamps as its light source. A proposal of the new optical design of detector using Ultraviolet Light Emitting Diodes (UV-LEDs) as the light source and Digital Micromirror Device (DMD) also requires new design of the mechanical components associated with it. The optics bench is the main structural component of the detector system on which the detector optical components are mounted. The work in this thesis focuses on the mechanical design of the optics bench assembly of the UV-LED detector.

1.1 Motivation

The current detectors used in liquid chromatography instruments utilize deuterium lamps as the light source and use a mechanically moving grating to select wavelengths. The design of a new detector for LC systems incorporating UV-LEDs instead of the traditional deuterium lamps will eliminate some of the drawbacks with the current detector and meet the future needs of customers by using new technologies. The deuterium lamp is large in size, expensive, have excessive heat generation, use more power and have short lifecycles (2000hrs). Due to high power and thermal management requirements, the current detector also has lot of unused empty space which helps in better cooling of the device. The mechanical grating used to select wavelengths is also limited in its frequency and the resolution to which it can separate wavelengths. Hence there is an opportunity of miniaturization of the device and to overcome the above limitations by having a new detector system that will make use of new technologies such as Ultra-Violet Light Emitting Diodes (UV-LEDs) and Digital Micromirror Device (DMD) instead of deuterium lamps and mechanical grating respectively. UV-LEDs are a cheaper, smaller and more efficient light source which offer a number of benefits including exceptional lifecycles and reliability, which make them the ideal choice for the next iteration of liquid chromatography detectors. Low wavelength UV-LEDs are an emerging technology and their development is motivated by their possible use in technologies such as sterilization and curing in lithography. Their only limitation is that a single UV-LED emits light in a narrow wavelength spectrum (about 20nm) when compared to UV lamps which have a wider spectrum range (approximately 180 – 700nm). Therefore, an array of LEDs will have to be used to cover the spectrum of the wavelength desired for testing samples in the detector. DMD which is an opto-electro-mechanical device, is smaller and lighter than mechanical gratings and can be used in combination with a diffraction grating to separate light of different wavelengths into finer resolution and at a far higher frequency. A detector design incorporating UV-LEDs and DMD with a modular architecture, where the LEDs can be easily replaced depending on the wavelength required is expected to deliver comparable or even better performance than the current detector.

1.2 Objectives

The primary objective of this project was to design and develop a new detector instrument with increased efficiency while incorporating new technologies such as UV-LEDs and DMD. Specifically, this encompassed three key objectives

- Design the optical system
- Develop the product architecture
- Design the mechanical components of the detector.

After the optical layout of the detector is defined, both the product architecture and target market decided, the mechanical design of the detector is taken up. In any optical instruments the relative positioning and orientation of the optical components are crucial as the components are very sensitive to changes in ambient environment, vibration, shock or impact loads, temperature variation, changes in refractive index and density of air, etc. Therefore it is very important to build an enclosure system around the sensitive optical components that can provide a rigid base on which the components can be individually mounted and aligned in precise fashion with long-term stability. Given the above reasons, the optics bench assembly is a very important structural component of the detector system. So as a starting point of mechanical design of the UV-LED detector, this thesis discusses the mechanical design of optics bench assembly in detail.

1.3 Scope

The scope of the project is limited to building a technological basis and a foundation on which detailed development of UV-LED based detector can be taken up in future. The scope of this thesis is limited to mechanical design of the optics bench assembly. This includes designing the optics bench enclosure according to the optical layout and functional requirements, finding the suitable material for the optics bench, determining the best suited and cost effective manufacturing process and corroborating engineering design choices with the appropriate engineering analysis.

1.4 Task Division

Each team member took the lead on one of three aspects of the detector design and development process and was responsible for the work done in that area. Daniel Gillund worked on optical design and developing the operational theory of the optical system, Saksham Saxena worked on customer segmentation and developing the product architecture. The author of this thesis worked on the mechanical design of the optics bench. The three thesis taken together would act as a reference and a basic guidance to start the development of mass produced consumer version of UV-LED based detector

CHAPTER 2: TECHNOLOGICAL BASIS FOR THE UV-LED BASED LIQUID CHROMATOGRAPHY DETECTOR

2.1 Liquid Chromatography - Brief History

Liquid Chromatography technique was discovered by Russian botanist Mikhail Tswett during 1900's. He used an open glass column packed with calcium carbonate and alumina particles to separate plant compounds (leaf pigments) during his research of chlorophyll. During the experiment he poured the sample, a solvent extract of homogenized plant leaves, into the column and allowed it to pass into the particle bed. This was followed by pure solvent. As the sample passed down through the column by gravity, different colored bands could be seen separating because some components moved faster than others due to differing strength of each compound's chemical attraction to the particles. In this process the compounds contained in the sample distribute or partition differently between the moving solvent, called the mobile phase, and the particles, called the stationary phase. This causes each compound to move at different speed thus creating different colored bands relating to different compounds that were originally contained in the sample [1]. Tswett coined the term "Chromatography" (from the Greek words Chroma, meaning color and Graph, meaning writing) to describe the experiment.

The works of Nobel Prize winners Archer John Porter and Richard Laurence Millington brought further development in chromatography in 1952 when they established the basis of partition chromatography and also developed plate theory.

2.2 Liquid Chromatography (LC) Techniques

Liquid chromatography techniques can be broadly classified into planar and columnar techniques. In both of the techniques the sample must be first dissolved in liquid that is then transported either onto, or into, the chromatography device. The column technique is the most powerful and has highest capacity for sample.

2.3 High-Performance Liquid Chromatography (HPLC)

In early liquid chromatography systems, high pressure of about 35 bar was used to generate the flow in packed columns. These systems were known as High-Pressure Liquid Chromatography or HPLC. The 1970s saw tremendous improvement in HPLC technology which could develop pressures up to 400 bar and incorporated improved injectors, detectors and columns. With continued advances in performance with technologies such as smaller particles and higher pressures the acronym remained the same but the name was changed to High-Performance Liquid Chromatography (HPLC).

HPLC systems are one of the most powerful instruments used in analytical chemistry today as they can easily identify compounds in trace concentrations as low as parts per trillion (ppt). It has the ability to separate, identify, and quantitate the compounds that are present in any sample that can be dissolved in a liquid and find its application in many industries such as pharmaceuticals, food, cosmetics, environmental matrices, forensic samples and industrial chemicals.

2.4 Ultra-Performance Liquid Chromatography (UPLC)

In the last decade, advancement in instrumentation and column technology led to significant increase in resolution, speed and sensitivity in liquid chromatography. A very high level of performance is achieved by using columns with particles as small as 1.7 microns and instrumentation with specialized capabilities designed to deliver mobile phase at about 1000 bar. This new system holistically created with updated capabilities is called Ultra-Performance Liquid chromatography (UPLC) technology. The UPLC system consists of 4 components - a solvent pump, a sample injector, a stationary phase or 'column' which allows the separation, and a detector to analyze the separating components.

2.5 Technology of Current Detectors used in Liquid Chromatography

Liquid chromatography currently uses two major classes of detectors- bulk property and specific property detectors. The bulk property detectors measure the bulk physical property of the column discharge and specific property detectors measure a physical or chemical property of the solute. These two major classes of detectors can be further divided into following subclasses

- Bulk Property Detectors
    - Refractive Index Detector
    - Electrochemical Detector
    - Light Scattering Detectors
- Specific/Solute Property Detectors
    - UV-Visible Light Detector
    - Fluorescence Detector

- Mass Spectroscopic Detector

2.5.1 UV-Visible Detectors

These are specific/solute property detectors which operate in the UV and visible light spectrum by either using filters to get a specific wavelength or by splitting the incident light (using a prism or diffraction grating) from the light source before or after it has passed the sample and measuring the intensity after it has gone through the sample to calculate absorbance of the sample.

These type of detectors can be further subdivided into 2 categories

Fixed Wavelength Detectors

The fixed wavelength detectors are simple in design and construction. They use a narrow band pass optical filter to get monochromatic light from the source for detection and therefore do not need to split the light.

Variable Wavelength Detectors

Variable wavelength detectors split light into its constituent spectrum using a prism/diffraction grating. Listed below are the two major types of variable wavelength detectors; Scan and Photodiode Array detectors.

- **Scan Detectors**

  In Scan detectors, either the photo-detector or the prism/diffraction grating is moved via motors to allow for potentially monitoring the sample at each separate wavelength. However, because of the inertia of the prism/grating and motor mechanism, it is not possible to switch between wavelengths at very high speeds. An example of a commercially available scan detector is the

Waters® ACQUITY UPLC® Tunable UV (TUV) Detector, which is a tunable, dual-wavelength UV/Visible detector.

- **Photodiode Array (PDA) Detectors**

  In PDA detector, light after passing through the sample is split into its constituent wavelengths and are made incident on an array of photodiodes to allow the simultaneous monitoring at many different wavelengths. Compared to other detectors, this one is relatively expensive due to the presence of photodiode array.

Most of the above detectors currently use gas discharge lamps, for example deuterium arc lamp or incandescent lamps as the light source, both of which produce a continuous spectrum

2.6 Overview of the Technology of the Proposed Detector

The optical design and technological basis of the proposed UV-LED detector is discussed in detail by Gillund [2]. The proposed detector, which is designed to be compatible with the HPLC/UPLC system, will have a bank of LEDs as the light source, which would be modular both from manufacturer and end user standpoint. These LEDs based on aluminum nitride (AlN) substrate will emit light in low UV range and emit a limited range of wavelength as compared to the deuterium UV lamp. To cover a broader range of wavelength, the detector will have up to 11 LEDs, which will allow the user to easily switch out LEDs resulting in any combination of peak wavelengths between 210 and 320nm. The presence and concentrations of particular substances in a sample can be determined by recording the amount of UV radiation absorbed at one or more particular wavelengths. The light from LEDs and the an onboard mercury arc calibration lamp will be transmitted to the light slit at the optics bench assembly using fused silica fiber optics. The light slit has a single aperture measuring 1mm long and 40 microns wide, which will allow light to be projected onto a spherical holographic grating. This grating will diffract the light according to wavelength and focus it onto a Digital Micromirror Device (DMD). The DMD will be used to select a single wavelength or a range of wavelengths and reflect it towards a spherical mirror. The wavelengths which are not selected will be directed onto a light dump. The light incident on the spherical mirror will be reflected toward the beam splitter, which, in turn, will direct a small portion of the light toward reference photodiode and the remaining light will be directed to the main photodiode through the flow cell. The main function of the reference photodiode is to enhance the signal to noise ratio of the processed data by cancelling out most forms of noise directly. The new detector will be a versatile instrument, with similar or improved capabilities as compared to both the TUV and the PDA, although within a smaller range of wavelengths. The specifications of the UV-LED detector are shown in Table 1.

Table 1: Specifications of UV-LED detector [2]

Specifications	**UV-LED DETECTOR**
Wavelength Range	Variable within 210-320nm
Sampling Speed	Variable from 80 Hz – 9.5 kHz
Noise level	6.5×10^{-6} (shot noise, no filter)
Bandwidth	Variable from 1 – 110nm
Resolution/Accuracy	± 0.2 nm
Irradiance of source	Variable up to 1.5μW nm^{-1} cm^{-2}
Self-referencing	Yes
Self-Calibration	0.05 sec. any time during run
Start-up time	< 1min

CHAPTER 3: DESIGN CONSIDERATIONS FOR OPTICS BENCH

3.1 Material Selection

Attributes of a specific material are a unique set of physical, mechanical and chemical properties that characterizes the material. The selection of material is decided by the specific set of attributes possessed by the materials that are required for an intended service. The material selection process for mechanical design can be broadly summarized as identifying the desired attributes as specified by the design and then comparing it with those of real engineering materials to find the best match. During the initial stage of material selection, it is important to start with the entire breadth of materials in mind to avoid missed opportunity of utilizing new innovative materials that can have better properties and performance, than conventional materials. Michael F. Ashby laid out a detailed and systematic method of material selection during mechanical design process [3]. The Ashby Material Selection methodology consists of four steps:

- Translation of design requirements to quantitative and qualitative terms such as function, constraints, objectives and free variables
- Initial Screening of materials based on derived attribute limits from constraints
- Ranking the screened material based on Material Index, which is a criterion of excellence that maximizes or minimizes the objective
- Final screening of materials based on supporting information such as availability, cost, behavior in working environments for top ranked material

3.1.1 Translation

Any engineering component has a multitude of functions such as; supporting a load, conducting heat, containing pressure, etc. These functions must be achieved while subjected to certain constraints laid down by the design such as maximum dimensions, thickness, maximum load capacity and so on. During the design process the designer is looking to achieve his or her design objectives (such as making the part lighter or cheaper) and to achieve these objectives, he or she is free to manipulate the variables which are not constrained by design requirements. These are called the free variables. Therefore, the first step of material selection is to reinterpret the design requirements in terms of the function, constraint, objectives and free variables.

3.1.2 Screening

Initial screening eliminates the materials which do not meet the basic requirements set by the constraints. These constraints are known as the attribute limits. Screening is done with the help of material selection charts which plot a combination of properties of interest, (for instance Young's modulus versus density or strength versus density); by mapping out the fields in property-space occupied by each material class, and the sub-fields occupied by individual materials. Attribute limits are plotted on material selection charts as horizontal or vertical lines. The material lying in the optimal region defined by the attribute limits matches the design requirements and has potential to be used in the final product/design.

3.1.3 Ranking

In order to rank the screened candidates an optimization criteria known as Material Indices is derived which measures how well a material matches the design requirements. It is a property or a group of properties that defines performance and therefore maximizing material index will maximize the performance for a given design.

3.1.4 Supporting Information

After ranking and shortlisting the top candidates which satisfies all design constraints and meets the objective requirements, other details are necessary for selecting the final best materials for the design. The details required are corrosion behavior in a particular environment, information on availability and pricing, aspects of the material's past history and established uses, in-house expertise or availability of machine tools for manufacturing, etc.

3.2 Manufacturing Process Selection

Similar to the material selection process, the manufacturing process is selected by translating the design requirements into function, constraints, objectives and free variables. Function defines what the final finished product is intended to do. Constraints can be set based on design requirements such as material, shape, mass, section thickness, tolerance requirements and annual production volume. Objectives define which parameter of the manufacturing process (cost, quality, time, etc.) needs to be maximized or minimized. Free variables are usually the choice of manufacturing process or chain of manufacturing processes that can meet the objectives while also satisfying the constraints. While performing the initial screening, processes which do not meet the basic design requirements are eliminated. Selection charts such as process-material matrix, process-shape matrix, property bar chart are used to select the appropriate manufacturing process. Additional information such as accessibility and infrastructure availability for a particular manufacturing process are also considered while selecting the best suited manufacturing process.

3.3 Design for Assembly and Serviceability

The guidelines for Design for Assembly (DFA) and Design for Serviceability (DFS) are discussed below

- In an assembly, a minimum number of parts required for proper functioning of the product should be used [4]
- Parts must be designed which are easy to align and assemble. Design of components should be such, that there is little or no resistance to insertion and chamfers should be provided to guide the insertion of two mating parts. Generous clearance should be provided and care must be taken to avoid clearances that will result in a tendency for parts to jam or hang-up during insertion
- Common parts, processes, and methods should be standardized across all models and even across product lines to permit the use of higher volume processes that normally result in lower product cost.
- A part must be designed such that it is located before being released. A potential source of problems arise when a part must be released at the place of its assembly before it is positively located. Under these circumstances, reliance is placed on the trajectory of the part being sufficiently repeatable to locate it consistently.
- Wherever possible, the necessity of holding parts down to maintain their orientation during manipulation of the subassembly or during the placement of another part must be avoided.
- For manual assembly, both access and vision should not be restricted, and for automated assembly, insertion should be in a straight line from above.

- Problems and issues related to manufacturability, reliability, serviceability in the current product must be addressed by understanding the problems with the previous models to prevent repeating the same mistakes [5].
- The assembly sequence must be concurrently engineered while designing the product. Designing for easy parts fabrication, material processing, and product assembly is a primary design consideration. Even if labor cost is reported to be a small percentage of the selling price, problems in fabrication, processing, and assembly can generate enormous overhead costs, cause production delays, and demand the time of precious resources.
- Overconstraining an assembly leads to high tolerance demands and also induces stress in the assembly. Overconstraints are also costly, causing quality problems and compromising functionality because the design will work only if parts are manufactured with extremely tight tolerances. On the other hand, under-constraining will have one or more unfixed degrees of freedom and thus results in loosely assembled parts. Therefore it is important to avoid over-constraining or under-containing the assembly [6].
- The parts must be designed such that there is an unobstructed assembly path for entry into the product. This prevents any damage to the part or product during the assembly. There must also be unobstructed access for tools and the tool operator, whether that is a worker or robot arm, for assembly and repair. Care must be taken that there are no awkward contortions to assemble each product manually, which can lead to worker fatigue, slow throughput, poor product quality, and even worker injury [5].
- Assembly should be designed such that the individual components/sub-assemblies are independently replaceable. This gives the advantage of easily replacing parts without having to remove other parts first. This makes the order of assembly more flexible because parts can

be added in any order. Another advantage of independently replaceable parts is the ease of adding options later, either in the factory or in the field. In terms of supply chain, this helps to cope with part shortages, allowing the rest of the product to be built and the parts which are not available to be added when they arrives.

- The assembly sequence must be designed so the component with lowest mean time to failure is assembled at the end (particularly for assemblies for which the components are not independently replaceable) and must be easiest to remove from the assembly so that it can be easily replaced without much hassle.
- Assembly should be designed to easily accommodate future upgrades and other part options without a complete redesign. This increases overall product life by adding future upgrades and helps generates more profit even in late stages of the product lifecycle. Considerations include allowing space for added parts, mounting holes, part access, tool access, software reconfiguration, extra utility capacity, etc.
- The product architecture should be structured into modules and sub-assemblies, as appropriate. Sub-assemblies can be built in specialized departments and tested separately from rest of the products, this streamlines the manufacturing and assembly process. Also sub-assemblies greatly simplify product testing, as individual sub-assemblies are already tested and do not require extensive re-testing during final assembly. It is also easier to identify failure modes and quality problems in a product with subassemblies and diagnostic attention could be focused to the sub-assemblies with highest likely probability of failures. Sub-assemblies also improve serviceability as the defective subassembly or parts can be easily repaired or replaced with new ones. Modular design concepts allows replacing obsolete modules with upgraded ones, increasing the product life and performance.

- Assembly using liquid adhesives and sealants should be avoided. Long drying times with adhesives and sealants can compromise flow manufacturing. Instead, alternatives such as screws or nuts coated with retention compound, fasteners with deformed threads, lock washers, compliant gaskets or even effective design strategy such optimal enclosures and built-in seals should be considered.

3.4 Thermal Management

Thermal distortion of components due to thermal gradients or due to change in temperature over time, is the most common cause of non-repeatability and dimensional instability in machine components. This negatively effects the functionality of the product due to thermally induced errors. Some of the guidelines to increase the thermal stability are discussed below [7] :

Sensitivity Reduction

- Structural design of components should be assembled in such a way that symmetric temperature distributions are achieved in symmetric structures which in turn reduces thermal distortions.
- Materials with a low coefficient of thermal expansion must be used to reduce variations in geometry due to variations in temperature.
- Components with the most critical temperature sensitivity must be located near the air inlet to provide the coolest air flow [8].

Management of heat sources

- The heat sources must be placed outside the controlled environment and unnecessary heat sources must be eliminated. Hot spots must be avoided by spot cooling using a small fan. Components that dissipate less heat are preferred over high heat dissipating components.
- Heat sources must be isolated from other sensitive components and the flow of heat removing fluids over other sensitive parts of the system must be prevented. The isolation of components with high heat dissipation can be achieved by placing those components near the enclosure air exits [8].
- The heat sources with the controlled environment should remain constant and the amount of heat dissipation should not vary over time.

Control of the machine environment

- The room/lab air temperature must be controlled to reduce temperature variations in the instrument.
- Heat leakage into or out of the instrument lab/room must be prevented to reduce variations in the room air temperature.
- The instrument structure should be isolated and the temperature of the metrology loop should be controlled.
- A temperature controlled fluid flowing over the subassembly/component must be used to regulate its temperature. The effect of viscous heating in high speed fluid flows should also be considered.
- The human body represents a heat source of about 100 watts and thus needs to be isolated by the use of insulating clothing such as gloves for precision applications.

- Dust can be kept out of the machine enclosure by pressurizing it by blowing air. The largest possible filter must be used in order to increase dust capacity and reduce pressure drop [8].
- Temperature control is the most reliable, effective and least expensive means to reduce thermal errors. The design challenge is figuring out how to provide sufficient control for minimal cost.

3.5 Shock Isolation

Mechanical shock is a sudden and severe non-periodic disturbance of a mechanical system which causes significant forces that may damage the system. Shock loads when applied to a portion or entire optical instrument may result in elastic or inelastic deformation of optical enclosure, impairment of optical alignment, and/or failure of fragile optical components. Such conditions are usually encountered during shipping, when for example the transportation truck encounters pothole or bump, or when someone accidentally drops the instrument while moving it. Some of the major causes of shock in a system are:

- Sudden change in the level of energy in the system by sudden introduction of energy
- Application of a sudden force
- Abrupt change in motion, velocity or acceleration of the system

The short duration transient loads called the shock pulse have complex wave shapes. To simplify the analysis the complex wave shapes can be approximated to a nearest simple wave shape with a known response. The input shock pulses are characterized by maximum amplitude, time duration and approximate shape. The majority of shock pulses encountered by objects can be categorized as half sine shock pulse, versed-sine shock pulse, rectangular shock pulse, triangular shock pulse, drop/freefall shock, velocity shock, acceleration impulse and force impulse. The shock resistance of an equipment is defined by its fragility, which in turn is expressed as the highest level of acceleration beyond which the equipment will fail to operate within specification. Shock mounts are used to absorb the input acceleration and release the shock energy over a broader time base, thus reducing the output acceleration. The shock mount shall not permit the output acceleration to exceed the fragility level of the most delicate component in an assembly. The instrument specifications generally define fragility in terms of acceleration in multiples of gravity. The shock level associated with normal manual handling of the optical instruments is around 3Gs. [9]

3.6 Vibration Isolation

Every structure has the tendency to vibrate at certain frequencies, which are known as natural or resonant frequencies. The natural frequency of a piece of equipment is given by Equation 1, where k is the stiffness and m is the mass of the equipment.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

Each natural frequency is associated with a certain shape, called mode shape, which the model tends to assume when vibrating at that frequency. Resonance is a condition in which a structure or component is excited by a dynamic load at one of its natural frequencies leading to large displacements and stresses in the component. For un-damped systems, resonance theoretically causes infinite motion. Damping, however, puts a limit on the response of the structures due to resonant loads.

The efficiency of flow of vibrational energy is quantified by transmissibility, which is defined as the ratio of dynamic output to dynamic input. In other words, transmissibility quantifies how efficiently a forcing vibration can produce an excited vibration.

Vibration isolation is attained by maintaining a proper relationship between the disturbing frequency and the system's natural frequency. Transmissibility measures the effectiveness of isolators in reducing vibration. Figure 1 shows transmissibility plotted against the ratio of disturbing frequency and the natural frequency of a system.

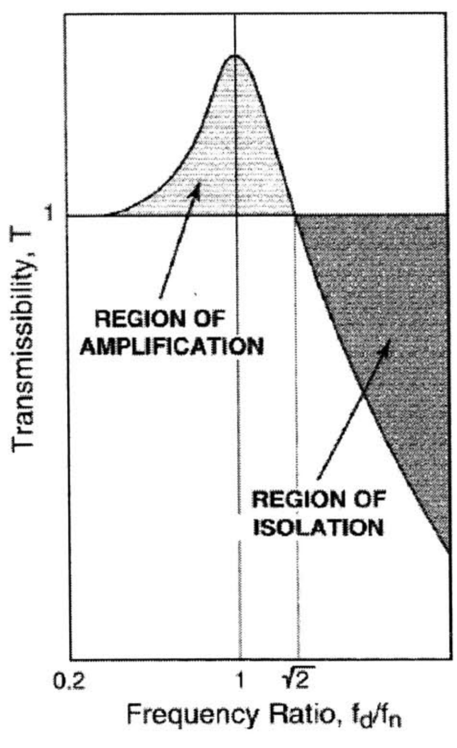


Figure 1: Transmissibility versus frequency ratio curve [10]

The plot shows, when the disturbing frequency is very low as compared to the natural frequency of the system the transmissibility is close to 1. When the disturbing frequency approaches the natural frequency, transmissibility is very high. This implies that the output is much higher than the input. When the ratio of the disturbing frequency and natural frequency is greater than $\sqrt{2}$, transmissibility is less than 1 and the system is isolated because the output is lower than the input. Elastomeric springs are commonly used for vibration isolation. Most of the vibration isolators also possess damping but in varying degrees. Without damping a system would continue to vibrate at its resonant frequency for an extended period of time even if the excitation load is removed. With damping the oscillations decay quickly as some of the excitation energy is converted into heat. The greater the amount of damping, lower is the transmissibility at resonance. Damping is advantageous when the system operates at or near the natural frequency as it reduces the peak response at resonance.

CHAPTER 4: MECHANICAL DESIGN OF THE OPTICS BENCH

4.1 Major Components

The optics bench assembly consists of optical and structural components. The major optical components of the optics bench assembly are:

- Light Entrance Slit
- Spherical Grating
- Digital Micromirror Device (DMD)
- Spherical Convex Mirror
- Beam Splitter
- Reference Photodiode
- Main Photodiode
- Flow cell

The detailed specifications and function of the optical components are discussed by Gillund [2]. The structural components of the assembly are

- Light dump/Shield
- Optics bench enclosure and cover
- Mounting brackets
- Fasteners

This thesis mainly focuses on design of structural components of the optics bench assembly.

4.2 Functional Requirements of the Optics Bench

The first step in the mechanical design of the optics bench is to define the functional requirements, which dictate the design decisions. The functional requirements of the optics bench casing are:

- Accurately locate the optical components and eliminate relative motion between any two components mounted on the bench
- Compatible with light of wavelength ranging from 150nm to 1000nm (UV to IR)
- Absorb/ Suppress any stray light or act as a light beam dump
- Isolate the optical components from:
    - Vibrations
    - Shock
    - External heat sources
    - Environmental temperature variation
    - Dust and airborne contaminants
    - Humidity
    - Corrosion due to solvents and chemicals
    - Abrasion/Erosion
- Conduct heat generated in the individual sub-assemblies and components, away from the optics bench assembly
- Feasible to manufacture and assemble
- Allows easy calibration and serviceability
- Effective service life cycle of over 15 years

4.3 Basis for the Design of the Optics Bench

The geometric shape of the optics bench is determined by the relative position and spatial arrangement of the individual optical components, which is turn is obtained from the optical layout of the UV-LED detector. The optical layout of the UV-LED detector as shown in Figure 2, is discussed in detail by Gillund [2] . The overall height of the optics bench is limited by the height of the detector module. Besides the spatial arrangement of the optical components, design for manufacturability, assembly and serviceability are other important factors that determine the form factor of the optics bench.

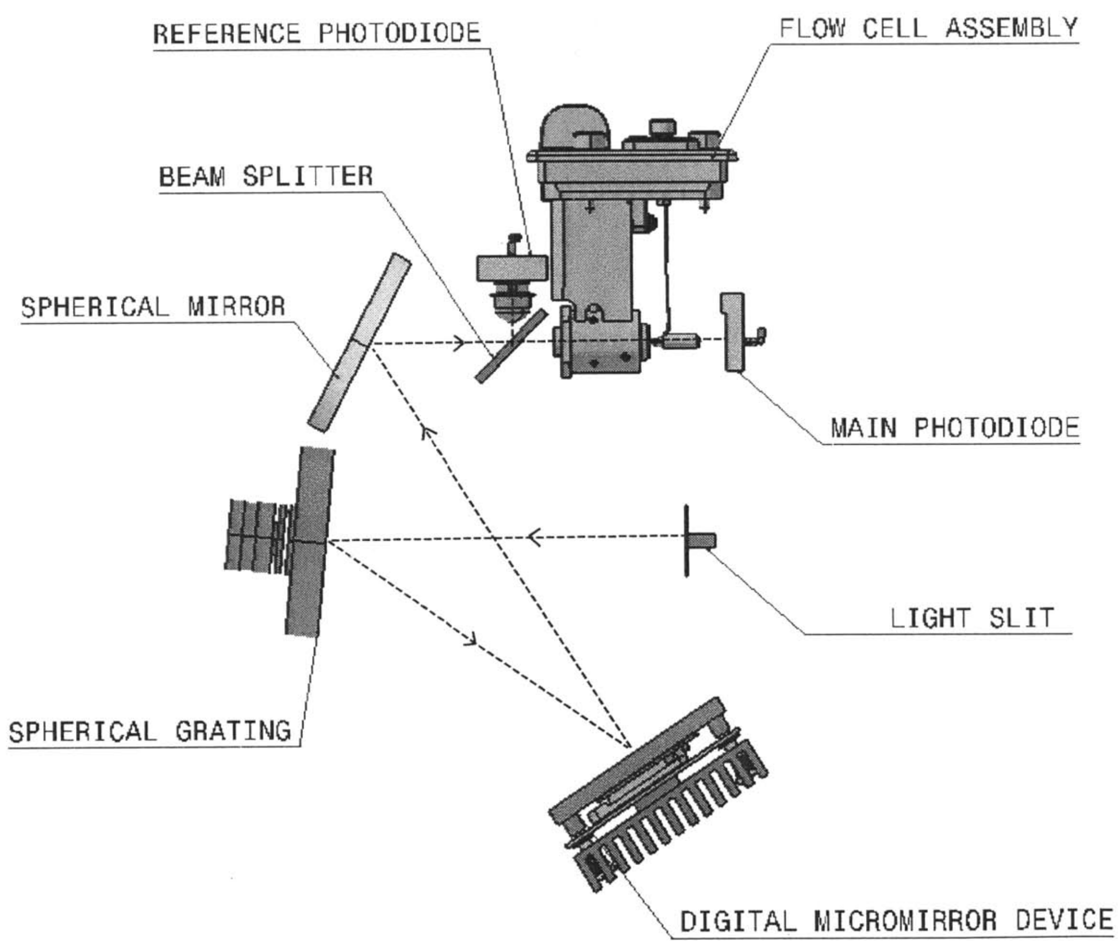


Figure 2: Optical layout of the UV-LED detector

Light dump, which absorb any stray light from light slit, DMD and spherical grating is also a part of the optics bench casing. Another feature of the optics bench casing is four equally spaced mounting feet. These feet are the attachment points of the optics bench assembly to the detector frame and also act as mounting points for shock and vibration isolators.

The side walls of the optics bench have slots through which the optical components enters into the optics bench casing. These slots are sufficiently bigger than the maximum dimensions of the optical components to provide easy accessibility and to prevent any damage to optical components during assembly.

The structural components of the optics bench assembly, which mainly includes the optics bench casing, cover, mirror and grating mounting mechanism, and mounting brackets for other optical components, was designed and assembled in CAD software Solidworks. First an initial approximate design was created according to the optical layout, satisfying the basic design requirements. The design is then iterated and continuously improved upon based on the principles of design for manufacturing, assembly and serviceability, results from engineering analysis, and discussions and design reviews with optical and mechanical engineers. The final design of the optics bench assembly can be seen in Figure 3. Note the rigid enclosure holding the optical elements together is the optics bench casing.

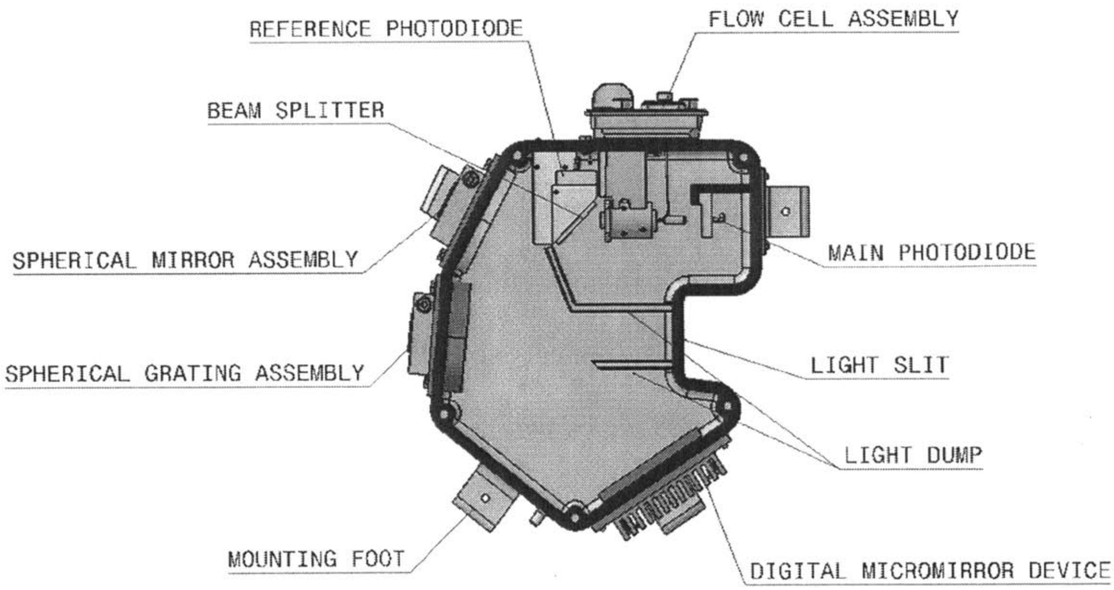


Figure 3: The optics bench assembly

4.4 Design for Assembly

The optics bench assembly is designed with the DFA guidelines in mind as discussed in Section 3.3. The product architecture of the optics bench assembly is structured into sub-assemblies. Major sub-assemblies are spherical mirror assembly, grating assembly, DMD assembly, beam splitter and reference photodiode assembly, and flow cell assembly. Division into subassemblies allows for individual calibration and testing of the mirror and grating assembly before being assembled into the optics bench. Subassemblies allow parts to be built in specialized departments or outsourced to a supplier with cheaper cost or better quality, without affecting other parts in the assembly. The selection of a suitable joining method of the subassemblies to the optics bench casing is equally important. Permanent joining methods are inappropriate because some of the optical components such as DMD and spherical grating have smaller mean time to failure than other components and will need to be replaced after much shorter their intended service lives. Therefore, the joining method must allow assembly and disassembly of all the components.

On the other hand, the components must be rigidly held in place during operation and must not loosen due to slight vibrations. The relative positioning and orientation of the optical components in an optical instrument is very critical. The optical components must also be individually mounted and aligned in a precise fashion on the optics bench. Given all the above constraints, threaded fastener are preferred for assembly. As shown in Figure 4, each optical component is located using two accurately machined locating pins and held in place on the optics bench with two fasteners. The components are directly bolted to the optics bench casing which has been precision machined and tapped holes. The locating pins are press fit in the machined holes on the optics bench. The pins help in easily aligning and orienting the part during assembly, reduces the number of fasteners required for assembly and shortens the overall assembly time. The locating pins have chamfer at the end to guide the insertion of the part during assembly.

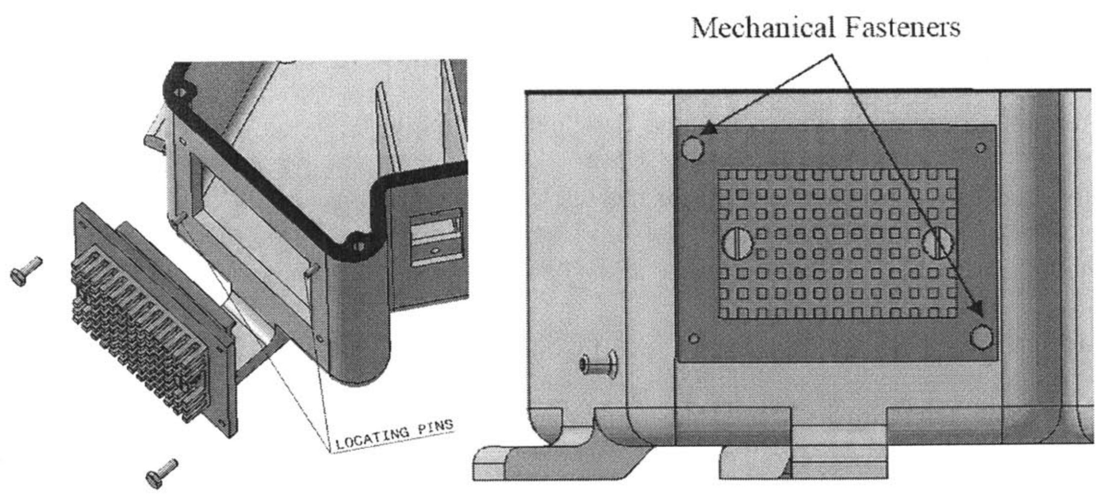


Figure 4: Design for assembly

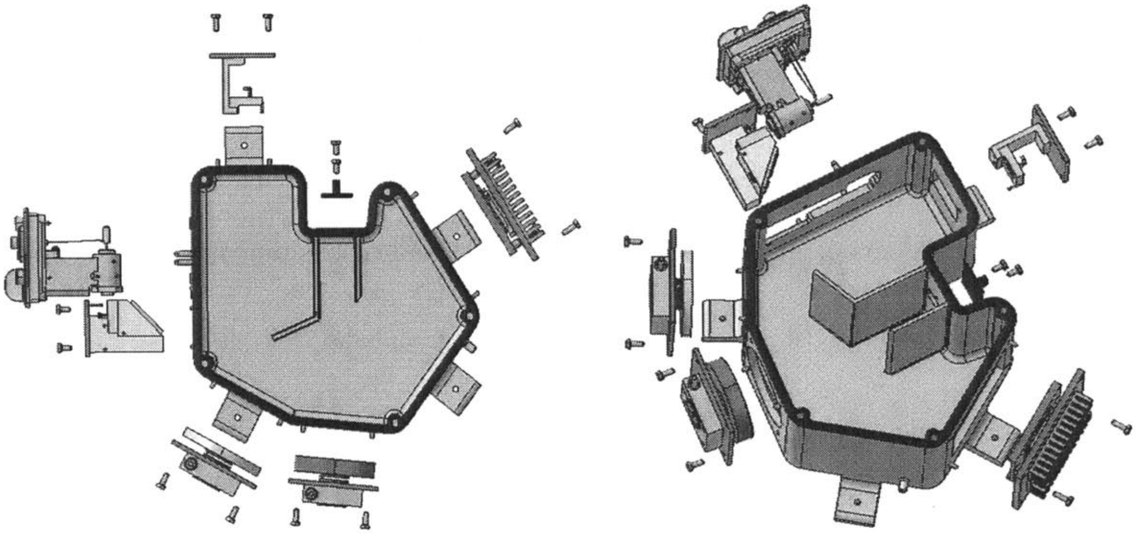
Since all the individual optical components will be assembled manually to the optics bench, parts are designed so that access and vision of the assembler is not restricted by any other part.

The fasteners are standardized in all the sub-assemblies for metric M4 size bolts except in the top cover. Standardizing fasteners helps in economies of scale and also simplifies the assembly process.

The slots in the optics bench casing have sufficient clearance to allow an unobstructed assembly path and to prevent damage to the optical components during assembly.

4.5 Design for Serviceability

The optics bench assembly is designed so that all the individual sub-assemblies are independently replaceable. This feature, shown in Figure 5, has multiple advantages. First, it allows sub-assemblies such as the grating assembly and mirror assembly to be calibrated and tested independently before being assembled to the optics bench. Second, this feature drastically improves serviceability of the instrument. A nonfunctional part in the assembly, can be removed for repairs or it can be replaced with a new part without removing any other components first. Third, the parts can be added in any order without any specific assembly sequence. Another advantage of using independently replaceable sub-assemblies is that any compatible future upgrade of the individual parts can be seamlessly integrated with the current system, increasing the product lifecycle of the detector. Finally, this design can also be used for any other detector variant with same optical layout but different part specifications.



(a) Top View *(b) Isometric view*

Figure 5: Design for serviceability

4.6 Material Selection

Material selection is an important step in achieving some of the major functional requirements as discussed in Section 4.2. To achieve the functional requirements, material of the optics bench should have:

- Low coefficient of thermal expansion to maintain dimensional stability
- High thermal conductivity to minimize distortion due to thermal gradient
- High stiffness to minimize vibration sensitivity
- High strength and toughness to minimize deformation during impact loading

The problem of thermal expansion, although critical, can be compensated by having an effective and robust thermal management system that maintains the average temperature of the optics bench within acceptable limits. Thermal gradients causes the distortion of the part for which compensation is not possible. So during material selection, minimizing the latter must be given priority. Vibration causes natural excitation which induces noise into the system due to which the functionality of the detector can be severely affected. Material cost and easy availability are also important considerations while selecting the final suitable material. The Ashby methodology of material selection is used to find the best suited material for the optics bench:

- **Translation**

As discussed in Section 3.1, the first step of the material selection process is to reinterpret the design requirements of the optics bench in terms of the function, constraints, objectives and free variables. The translation chart for material selection is shown in Table 2.

Table 2: Translation chart for material selection

FUNCTION	Support and protect optical components
CONSTAINTS	Optics bench shape and dimensions
OBJECTIVE	Maximize thermal conductivity, minimize vibration sensitivity, minimize deformation during impact loading
FREE VARIABLES	Material

- **Screening**

The ideal material of the optics bench should easily remove the heat generated in internal components during operation to prevent build-up of high temperatures inside the optics bench.

This can be achieved by having a material that has high value of coefficient of thermal conductivity.

As the first screening step, materials with coefficient of thermal conductivity smaller than 10W/mK are eliminated. As shown in Figure 6, only metals and majority of ceramics qualify as suitable materials after the first screening step.

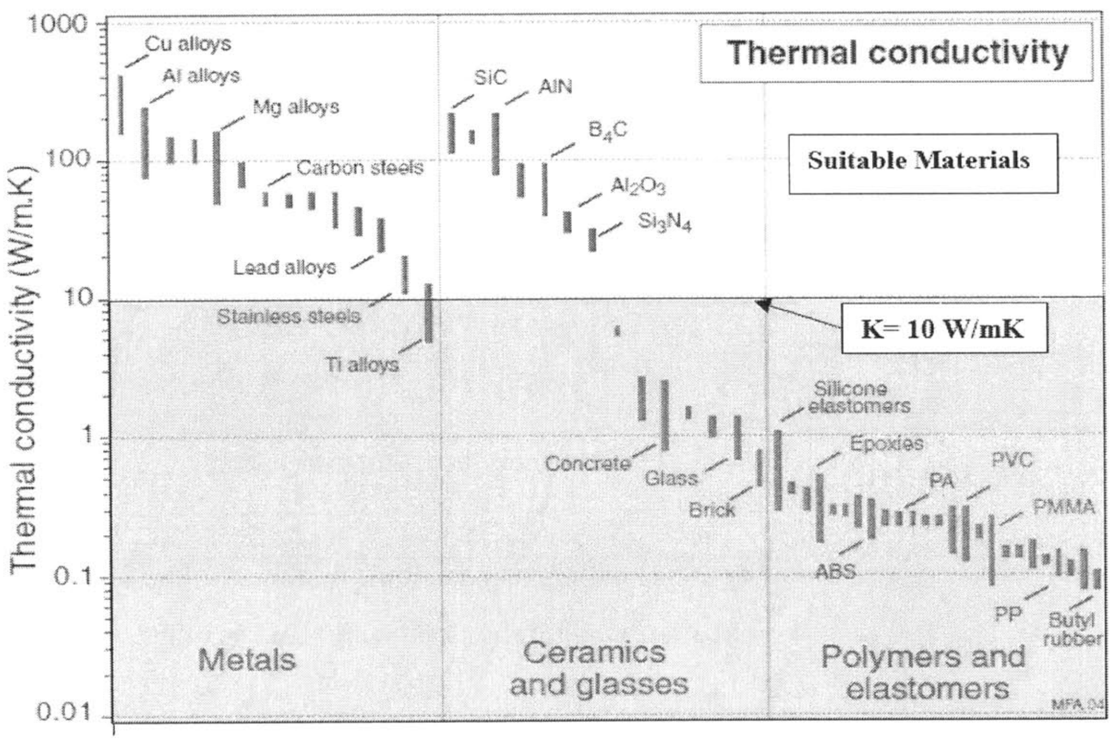


Figure 6: Thermal conductivity bar chart. Screening of materials based on thermal conductivity [3]

- **Ranking**

o **Material Index for Minimizing Thermal Gradient**

The performance index is found out by considering a simple case of one dimensional heat flow through the walls of the optics bench. The steady state Fourier law is given by Equation 2, where q is the heat flux, λ is coefficient of thermal conductivity of the material and $\frac{dT}{dx}$ is temperature gradient.

$$q = -\lambda \frac{dT}{dx} \tag{2}$$

The strain developed due to temperature gradient is given by Equation 3, where α is coefficient of linear expansion of the material and ΔT is the difference in temperature of the optics bench casing and the ambient temperature.

$$\epsilon = \alpha \, \Delta T \tag{3}$$

$$\frac{d\epsilon}{dx} = \alpha \frac{dT}{dx} \tag{4}$$

Equation 5 is derived by combining Equations 3 and 4, where $\frac{d\epsilon}{dx}$ is the measure of distortion due to thermal gradient.

$$\frac{d\epsilon}{dx} = q \left(\frac{\alpha}{\lambda}\right) \tag{5}$$

Now the thermal gradient can be minimized by minimizing the value of $\frac{\alpha}{\lambda}$ or selecting materials with large values of index M_1, which is given by Equation 6.

$$M_1 = \frac{\lambda}{\alpha} \tag{6}$$

To have good dimensional stability and minimize distortion due to thermal gradient, the material should have low coefficient of thermal expansion and high coefficient of thermal conductivity. Figure 7 shows that the value of the index $M_1 = \frac{\lambda}{\alpha}$ increases by moving towards the bottom right side of the chart. The attribute limits are set at λ = 10 W/mK and $M_1 = 10^7 \frac{\mu\, stain/K}{W/mK}$ to eliminate materials with low thermal conductivity and high thermal expansion. Metals such as aluminum, copper, tungsten alloys, silicon and technical ceramics such as tungsten carbide, silicon carbide, aluminum nitride satisfy the above criteria.

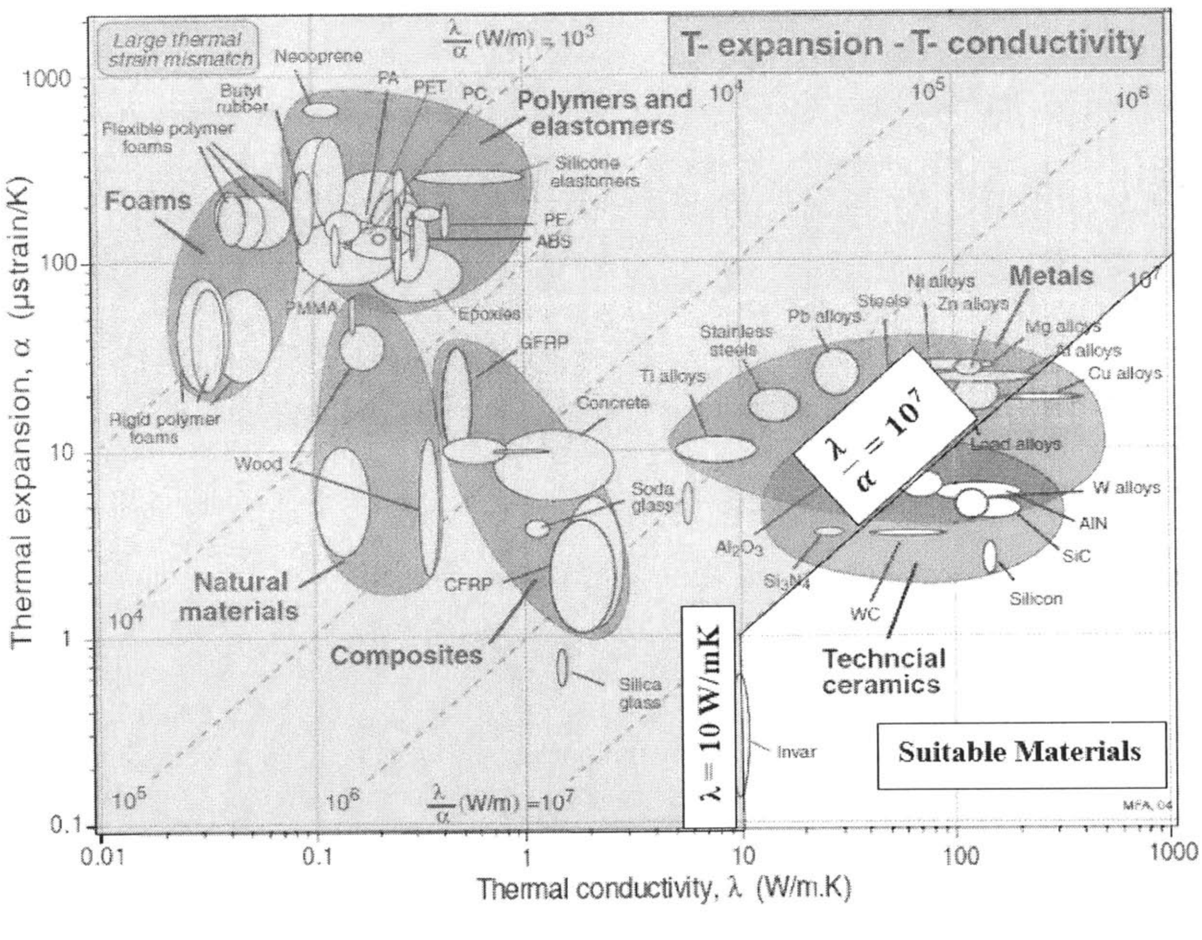


Figure 7: Thermal expansion versus thermal conductivity chart. Selection of material with good dimensional stability and low thermal distortion [3]

- **Material Index for Minimizing Vibration Sensitivity**

The sensitivity to the external excitation is minimized by maximizing the natural frequencies of the component. For the sake of simplicity, the optics bench is assumed to be resting on two mounting supports and excitation force acting through its center of gravity. This is equivalent to a light and stiff square beam of side b, subjected to three point bending load. Stiffness of the beam in the above condition is given by Equation 7, where F is the force acting on the beam, δ is the deflection of the beam, E is the Young's modulus of the beam's material, L is the length of the beam, I is the second moment of area given by $\frac{b^4}{12}$ or $\frac{A^2}{12}$, A is the cross-sectional area of the beam and C is a constant whose value depends on the type of the loading.

$$S = \frac{F}{\delta} = \frac{CEI}{L^3} \tag{7}$$

Mass of the beam is given by Equation 8, where ρ is the density of the beam's material.

$$m = \rho AL \tag{8}$$

Combining equation for stiffness and second moment of inertia with the mass equation we get Equation 9.

$$m = \left(\frac{12S}{C}\right)^{1/2} (L)^{5/2} \left(\frac{\rho}{E^{1/2}}\right) \tag{9}$$

The flexural vibrations have lowest frequencies and they are proportional to $\frac{E^{1/2}}{\rho}$ [3]. Thus the sensitivity to vibration can be minimized by selecting a material with large value of the index M_2 given by Equation 10.

$$M_2 = \frac{E^{1/2}}{\rho} \tag{10}$$

As shown in Figure 8, value of the index M_2 increases by moving towards the top left corner of the chart. The attribute limits are set at E = 1 GPa and $M_2 = 1\frac{GPa^{1/2}}{Mg/m^3}$ to eliminate materials of low stiffness. Some of the qualifying materials according to the above criterion are ceramics, majority of the metals, composites and some natural materials such as wood.

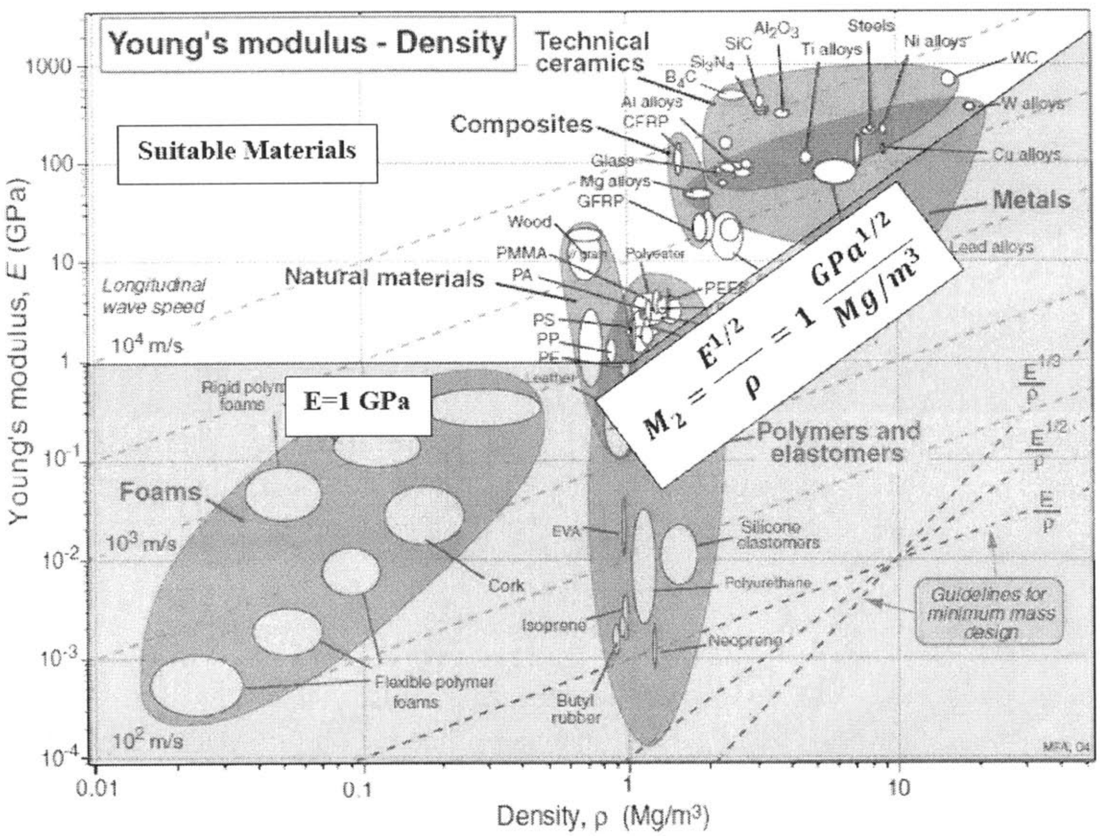


Figure 8: Young's modulus versus density chart. Selection of material with low vibration sensitivity [3]

o Material Index for Minimizing Deformation during Impact Loads

During impact loading, it is assumed that the optics bench of mass m falls from a height h under the influence of gravity. After contact with the floor the optics bench deforms due to stresses developed. The amount of deformation depends on the stiffness of the component. The change in potential energy U after the impact is given by Equation 11.

$$U = mgh \tag{11}$$

This energy is absorbed by the material through the deformation of the component. This is known as strain energy and is given by Equation 12, where σ is the stress developed due to impact loading, ϵ is the strain developed in the material, V is the volume of the part.

$$Strain\ Energy \propto \sigma\epsilon V \tag{12}$$

The Hooke's law relation is given by Equation 13.

$$E = \frac{\sigma}{\epsilon} \tag{13}$$

Substituting Equation 13 into Equation 12, gives the elastic strain energy per unit volume, the expression for which is given by Equation 14.

$$Elastic\ Strain\ Energy\ stored\ per\ unit\ volume\ \propto \frac{1}{E}\sigma^2 \tag{14}$$

The optics bench will be permanently deformed if the stress σ developed after impact loading exceeds the failure strength σ_f of the material. Therefore to prevent deformation, the stress developed in the part after impact loading must be less than the failure strength of the material. This constraint is shown by Equation 15.

$$\sigma \leq \sigma_f \tag{15}$$

The maximum strain energy that can be stored in the body without permanent deformation is known as proof resilience U_m, which is given by Equation 16. Therefore the objective is to maximize the maximum energy density or proof resilience of the body.

$$U_m \propto \frac{{\sigma_f}^2}{E} \qquad (16)$$

Thus the deformation after impact loading can be minimized, by selecting a material with large value of the index M_3, given by Equation 17.

$$M_3 = \frac{{\sigma_f}^2}{E} \qquad (17)$$

As shown in Figure 9, value of the index M_3 increases by moving towards the right of the chart. The attribute limits are set at E = 1 GPa and $M_3 = 100\frac{MPa^2}{GPa}$ to eliminate materials with low value of Young's modulus and low strength. Some of the qualifying materials according to these criteria are ceramics such as Tungsten carbide, Silicon Carbide, most of the metals, composites and some of the polymers such as PMMA, PC, Polyurethane, and Polyamide.

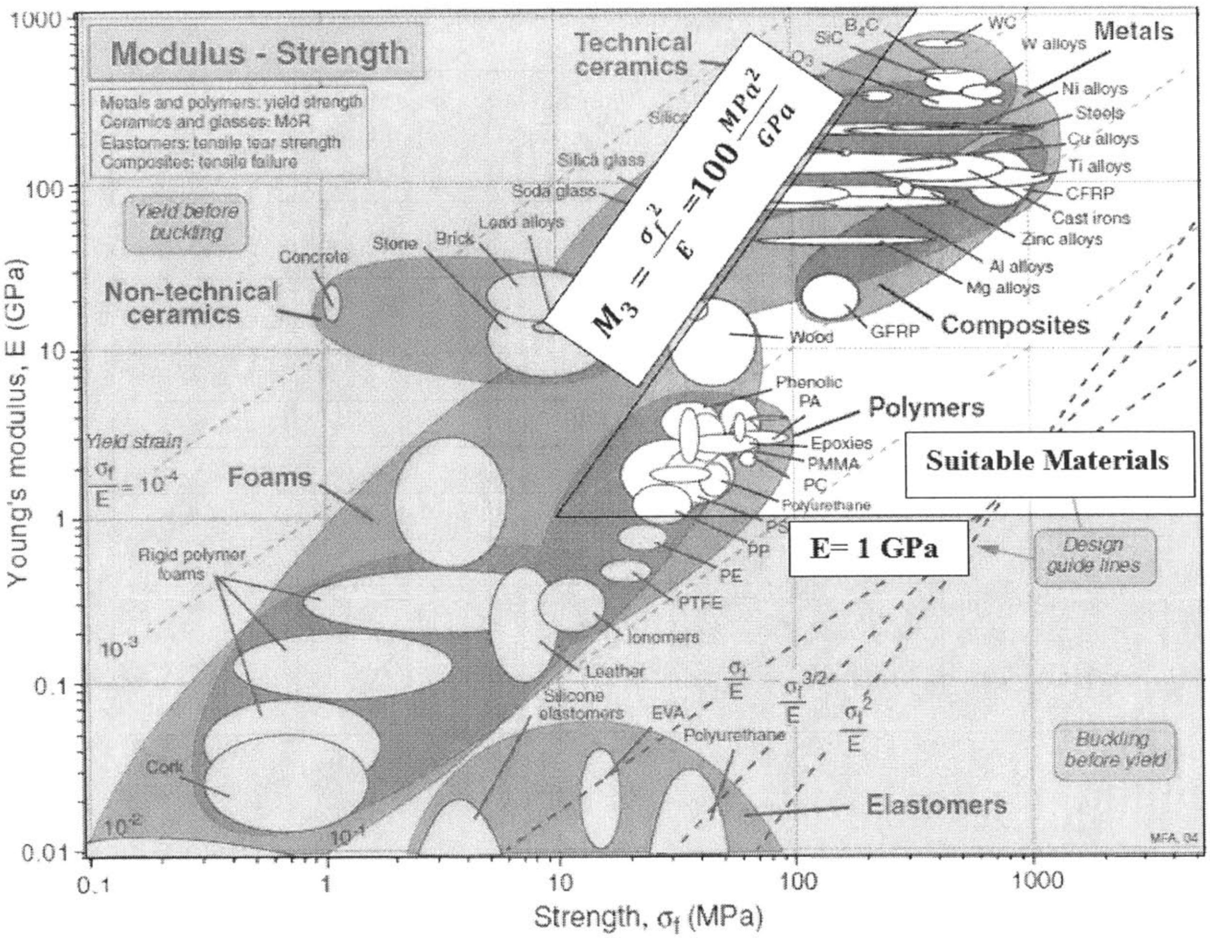


Figure 9: Young's modulus versus strength chart. Selection of material with high resistance to deformation during impact loads [3]

- **Material Properties Comparison**

The material properties of the top ranked materials along with some common materials are shown in the Table 3 for comparison. The values of the material indices M_1, M_2 and M_3 as shown in Table 4, are derived from Table 3.

Table 3: Mechanical Properties of top ranked and common materials [3]

MATERIAL	E (GPa)	Yield Strength (MPa)	Thermal Conductivity (W/mK)	Thermal Expansion (10^{-6}/K)	Density (10^3kg/m^3)
Silicon Carbide	350	3125	155	4	3.1
Aluminum Nitride	320	2335	140	5	3.29
Aluminum	72.4	170	151	21.4	2.67
Copper	130	265	275	17	8.93
Zinc	80	265	117	25	6
Steel	200	750	15	16	7.8
PEEK	4	80	0.25	133	1.31
Bulk Molding Compound (BMC) 940 [11]	9.5	28	13	30	1.89

Table 4: Material indices of top ranked and common materials

MATERIAL	$M_1 = \frac{\lambda}{\alpha}$ $\left(\frac{W/mK}{10^{-6}/K}\right)$	$M_2 = \frac{E^{1/2}}{\rho}$ $\frac{(MPa)^{1/2}}{Mg/m^3}$	$M_3 = \frac{\sigma_f^2}{E}$ $\frac{(MPa)^2}{GPa}$
Silicon Carbide	38.75	6.0	27902
Aluminum Nitride	28.00	5.4	17038
Aluminum	6.95	3.2	936
Copper	16.17	1.3	540
Zinc	4.68	1.5	878
Steel	0.94	1.8	2813
PEEK	0.002	1.5	1600
Bulk Molding Compound (BMC) 940	0.43	1.6	83

As clearly seen from Table 3 and Table 4, silicon carbide has the best overall properties for the optics bench application followed by aluminum nitride and aluminum. Polymers do not qualify mainly due to the poor ratio of thermal conductivity to thermal expansion, which will lead to distortion and dimensional instability at high operating temperatures.

- **Supporting information for material selection**

  - **UV Compatibility**

Since the detector uses UV-LEDs as the light source, one of the basic requirements of the optics bench material is to be UV compatible and resist photo degradation under long UV exposure. This is also necessary in order to have a long lifecycle of the optics bench since materials that are not UV stable will degrade over time and become brittle, crack, decolorize, warp, etc. UV compatibility can be drastically improved by coating the base material with other materials which prevent UV degradation and also absorb/suppress any stray or scattered UV radiation.

Ceramics and Metals are much less susceptible to UV based damage as compared to polymers [12]. Therefore ceramics such as SiC or AlN and metals such as aluminum are better suited materials for the optics bench than polymers.

  - **Material Cost**

Figure 10 shows the cost per unit weight of different material class. An approximate cost comparison (cost per unit weight) between aluminum and ceramics (SiC and AlN) shows that ceramics costs at least 5 times than that of aluminum alloys. This cost difference outweighs the advantages in properties that ceramics have over aluminum. Thus using ceramics as a material for optics bench is not practical due to its prohibitively high cost.

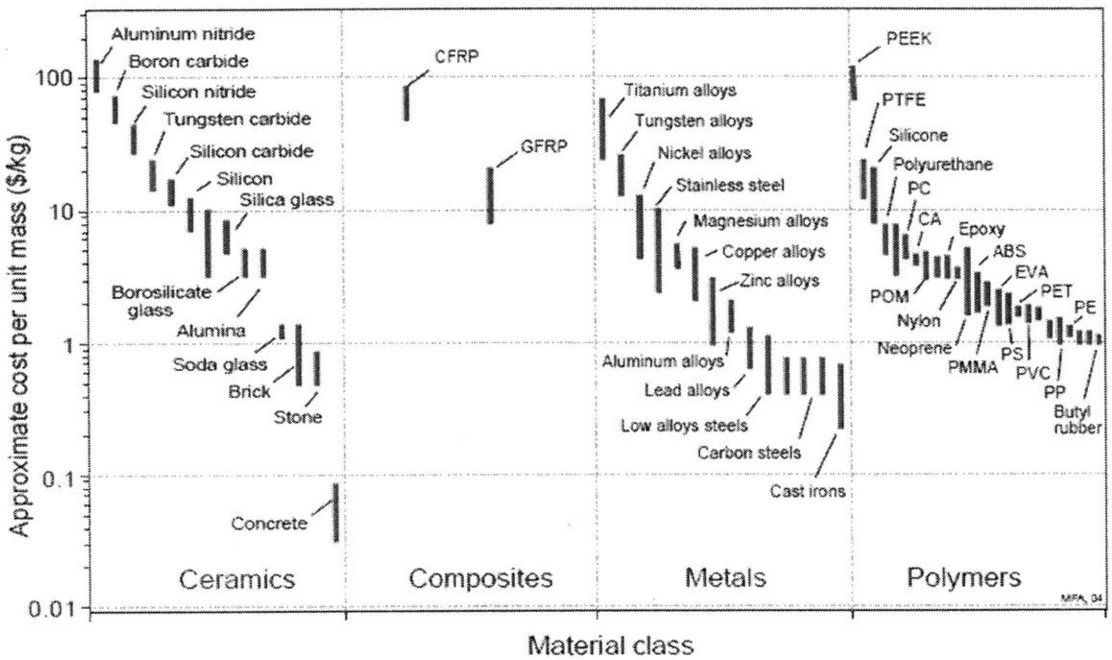


Figure 10: Bar chart of cost per unit weight of different material class [3]

o **Availability**

Aluminum and its alloys are more readily available and more widely used as compared to ceramics. The manufacturing infrastructure for aluminum is also well established and readily accessible and compared to ceramics aluminum processing is cheaper.

- **Selection of Aluminum Alloy**

The analysis in the previous section shows that aluminum is the best suited material for the optics bench taking into consideration a lot of factors such as strength, dimensional stability, vibration sensitivity and cost. Aluminum alloys have much better properties for opto-mechanical applications than pure form of aluminum. Some of the commonly used aluminum alloys are Alloy 1100, Alloy 2024, Alloy 6061, Alloy 7075 and Alloy 356. Out of these, Alloy 356 is the best suited alloy for general purpose optical instruments. The main alloying composition for aluminum 356 is 7% Silicon and 0.3% magnesium. The higher purity variant of the alloy (in terms of chemical composition) is designated with an A before the number 356. Some of the properties of aluminum A356 are [13]

- Good castability by sand, permanent mold and die casting methods making it an excellent candidate for intricate and complex castings
- Good machinability characteristics
- Moderate to high strength
- Excellent corrosion resistance
- Very good weldability characteristics

The common mechanical properties of aluminum A356 is shown in the Table 5.

Table 5: Mechanical properties of aluminum alloy A356 [14]

Material	Young's Modulus (GPa)	Yield Strength (MPa)	Thermal Conductivity (W/mK)	Thermal Expansion (10^{-6}/K)	Density (10^3kg/m^3)
Al A356	72.4	>165	151	21.4	2.67

4.7 Engineering Analysis

4.7.1 Drop Test

A drop test analysis on Solidworks simulation is carried out to test if the design of the optics bench assembly is robust enough to maintain its structural integrity when it is subjected to impact loads. As shown in Figure 11, the test is carried out by assuming that the optics bench falls freely on the base from height of 1000 mm on a rigid ground under the influence of acceleration due to gravity.

The testing specification is in accordance with the "Optics and Photonics-Environmental test methods - ISO 9022" (Appendix A, Method 33 Freefall test) [9].

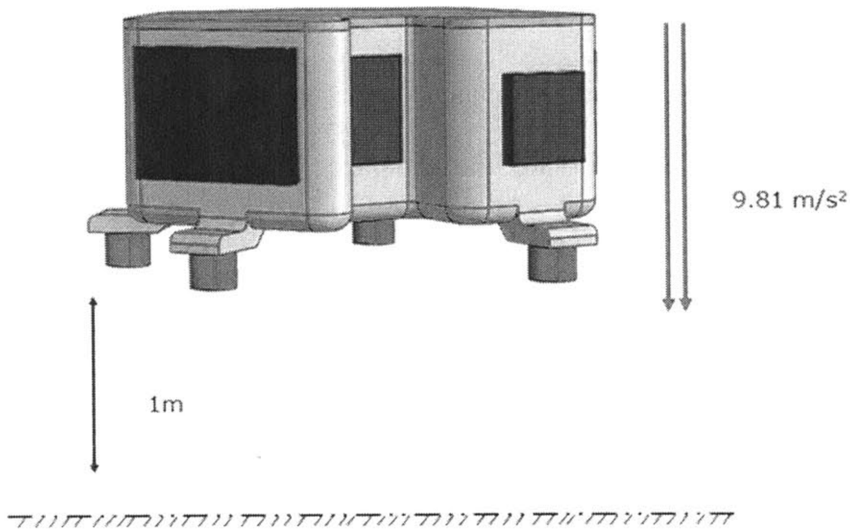


Figure 11: Drop test analysis of the optics bench

The amount of stress developed in the optics bench casing due to the impact loading is analyzed and compared with the yield strength of aluminum A356. The design of optics bench should be such that it not only maintains its shape and form after the impact but it also protects the delicate optical instruments that is mounted on it. To simplify the meshing and analysis, the optical components are modeled as cuboid with the same mass as that of original components. The first design iteration of the optics bench which is tested for impact loading has a wall thickness of 4mm. The results of the drop test on optics bench with 4mm wall thickness is shown in Figure 12. The results indicate that the maximum stress value developed is 233.6MPa. This value is much greater than the yield strength of aluminum A 356 which is around 170MPa. The results show that the maximum value of the stress is developed near the grating and mirror mounting area which will not only result in permanent deformation of optics bench but also damage the optical components.

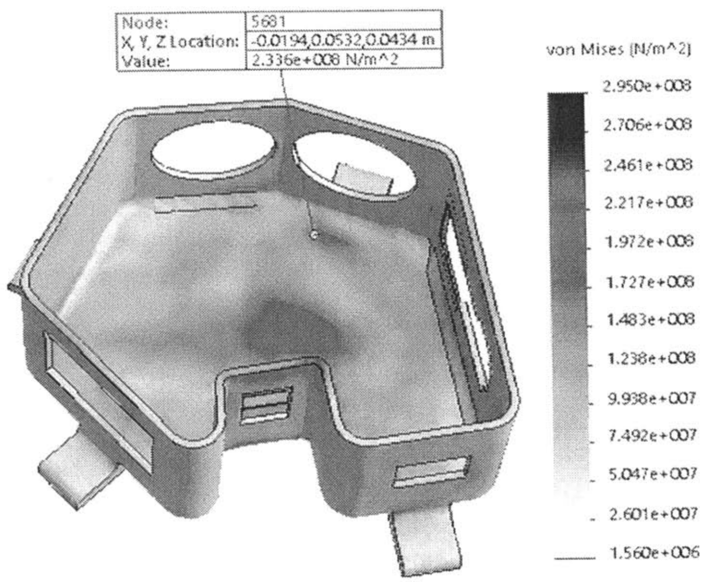
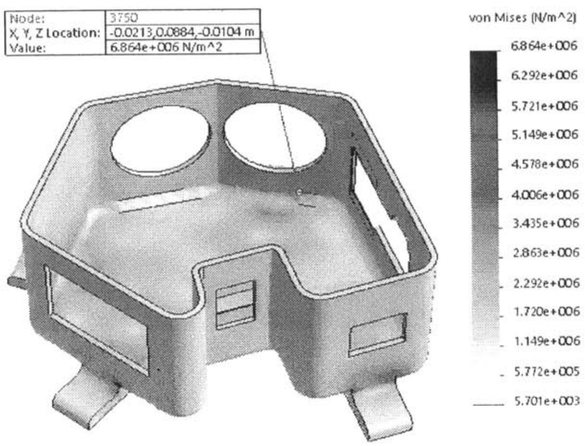


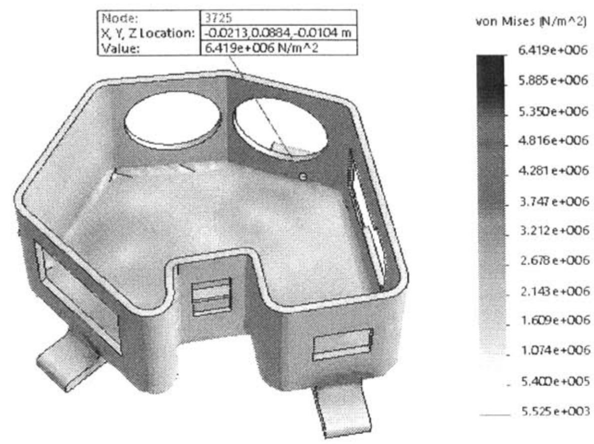
Figure 12: Drop test analysis of optics bench with wall thickness 4mm without shock mounts

Therefore shock mounts (shock and vibration isolators) must be used at the mounting points of the optics bench and also at the base of the detector frame to protect the delicate optical instruments in case of an impact. These shock mounts also act as vibration isolators for the instrument. For drop test simulation the shock mounts are modelled as a cylinder made of neoprene measuring 25mm in diameter and 20 mm in length. The results of the drop test analysis with elastomeric shock absorbers carried out for different wall thickness starting from 4mm to 8mm are shown in Figure 13. The results indicate significant reduction in the stress values. Figure 13 (a) shows that optics bench with 4mm wall thickness has maximum stress value of 6.864 MPa. This is much lower than the yield strength of aluminum A 356 (170 MPa). Optical glass can withstand tensile stresses of 6.9 MPa (1,000 psi) and compressive stresses of 345 MPa (50,000 psi) before problems or failure occur, thus the design objective must be to keep the stress levels lower than 6.9 MPa

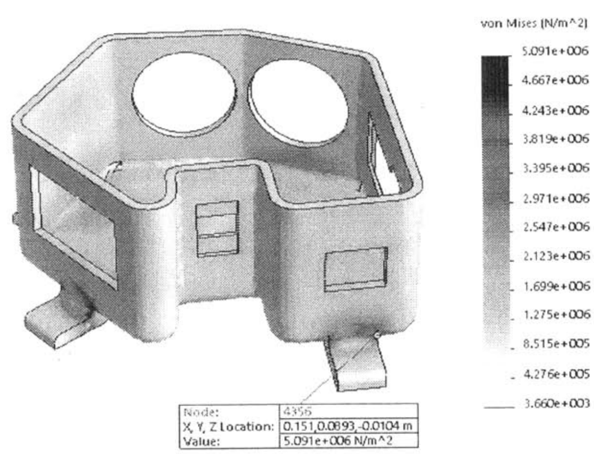
[15]. Further reduction in maximum stress values can be achieved by choosing the optimal wall thickness of the optics bench.



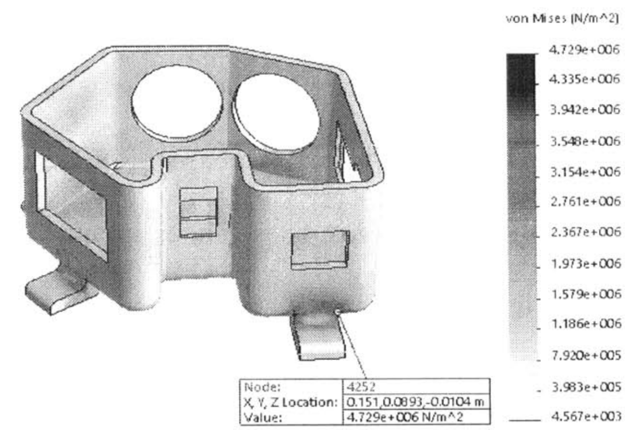
(a) 4mm wall thickness



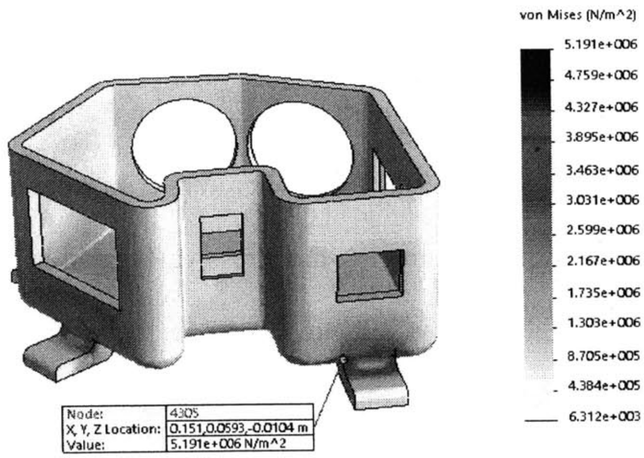
(b) 5mm wall thickness



(c) 6mm wall thickness



(d) 7mm wall thickness



(e) 8mm wall thickness

Figure 13: Drop test analysis of optics bench with shock mounts

The plot of maximum stress developed in the optics bench casing during impact versus the wall thickness is shown in Figure 14.

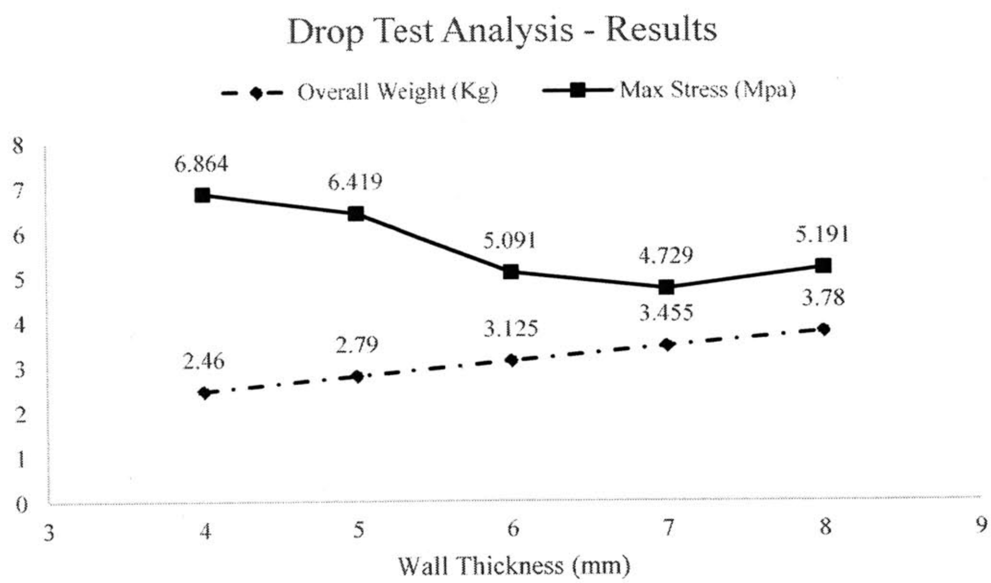


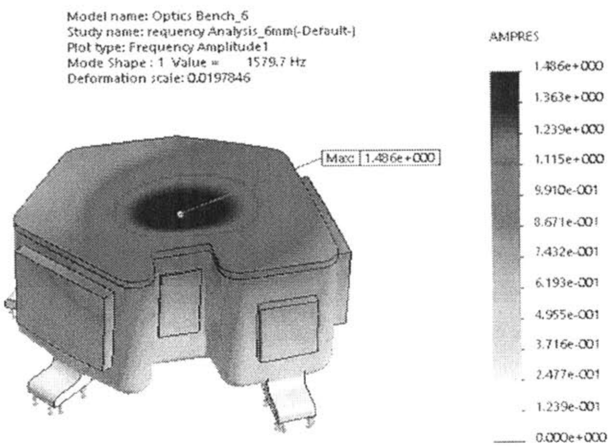
Figure 14: Variation of maximum stress during impact loading and overall weight of the optics bench with increasing wall thickness

The plot indicates that the maximum stress value in a drop test reaches a minima for a wall thickness of 7mm. The increase in wall thickness increases the overall weight of the optics bench assembly which in turn increases the material cost. Therefore a thickness value between 6 and 7 mm will be a good tradeoff between minimizing the stress values and keeping the weight of the part within acceptable limits. For a thickness value in this range, the maximum stress during impact in the optics bench assembly with shock mounts will around 5 MPa. This value is lower than the failure strength of the glass (6.9 MPa).

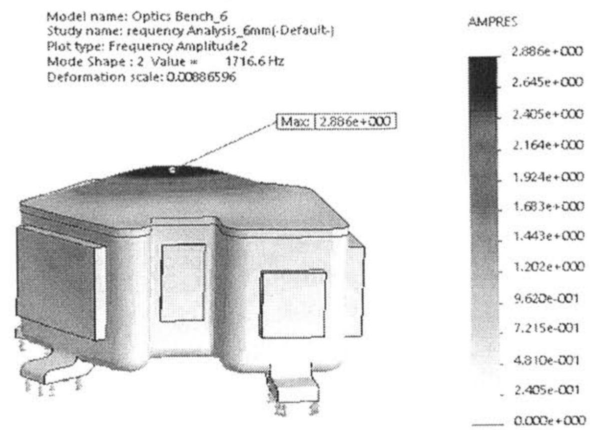
4.7.2 Vibration Analysis

Uncontrollable sources of vibration such as fans, air conditioners, pumps, motors, road and rail transportation, etc., can lead to vibration induced performance degradation in precision optical instruments. Since UV light has wavelength of around 0.2 microns, vibrations with amplitude even in sub-micron range can seriously hamper the performance of the detector by eclipsing valuable data under vibration induced noise. Therefore it is necessary to isolate the critically aligned optical components from the above sources of vibration disturbances. Resonance in opto-mechanical devices can be avoided by designing parts with high stiffness so that their natural frequencies of vibration are significantly higher than those of anticipated driving forces.

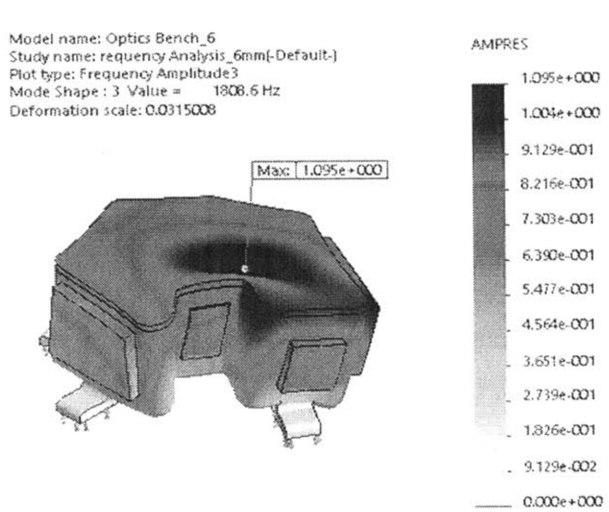
Frequency analysis was carried out in Solidworks to find the optimal wall thickness that maximizes the natural frequency and stiffness of the optics bench. In this analysis the mounting points of the optics bench were fixed and the bench assembly was made to vibrate in different natural frequency modes. The first five vibration modes of the optics bench assembly are shown in Figure 15. Out of these first five vibration modes, mode 3 is of major concern because the optical components vibrate in and out relative to each other. This mode will affect the performance of the detector because it changes the relative distances between the optical components which results in loss of resolution and sensitivity.



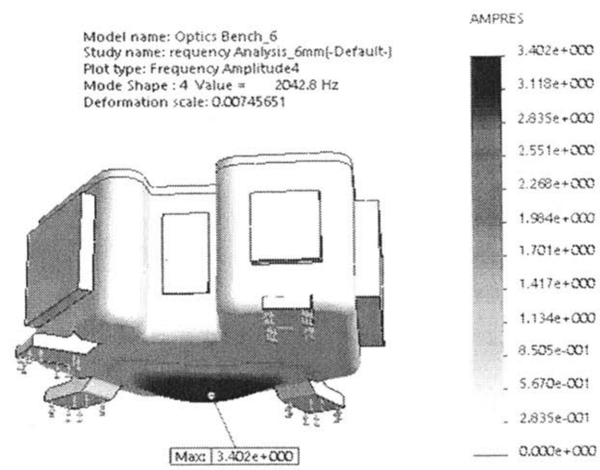
(a) Mode 1



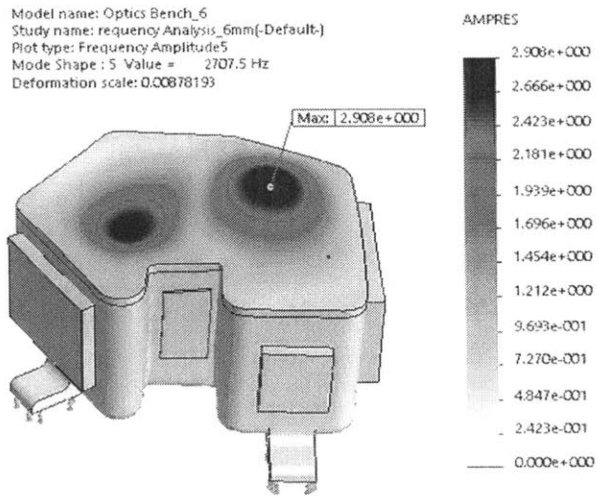
(b) Mode 2



(c) Mode 3



(d) Mode 4



(e) Mode 5

Figure 15: First five vibration modes of the optics bench assembly

The results of the vibration analysis shows the natural frequency of vibration of the optics bench assembly in different modes are all above 1400 Hz. This frequency range is much higher than the ambient vibration disturbances, which is typically in the range of 4-100 Hz range. Such large frequency differences between resonant and excitation frequencies prevent energy coupling between the optics bench assembly and its support structure. Thus the optics bench assembly is isolated from ambient vibration disturbances [16].

The variation of mode 3 (critical mode) natural frequency of optics bench assembly for different wall thickness of optics bench casing is shown in Figure 16. The components with high natural frequency of vibration have higher stiffness and are less sensitive to external vibration disturbances. Therefore the optics bench with optimal wall thickness will maximize the natural frequency of vibration.

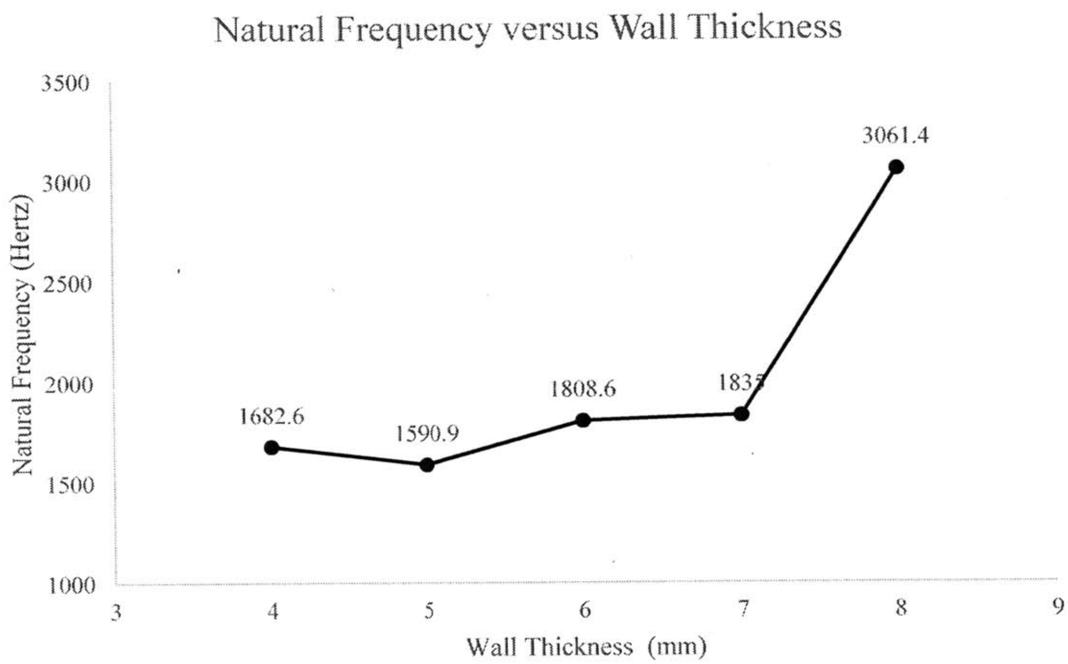


Figure 16: Variation of natural frequency of optics bench assembly in critical mode with optics bench casing wall thickness

The results of the frequency analysis show that increasing the wall thickness increases the natural frequency of vibration. The drop test analysis in Section 4.7.1 shows that a wall thickness of 8mm increases the stress values during impact/shock loading and also increases the weight as well as the material cost. A wall thickness between 6 and 7mm is a good compromise which leads to low stress during drop test, high natural frequency of vibration (around 1800Hz), and results in the weight of the optics bench which is within acceptable limits.

Based on the results of drop test and vibration analysis a wall thickness of 6.35 mm (1/4 inch thick) is selected for the optics bench. In terms of manufacturability, optics bench with 6.35 mm wall thickness can also be easily manufactured with conventional or advanced casting methods.

4.7.3 Vibration Isolation

A good design of the optics bench must have a natural resonant frequency as high as possible and it must be well damped. Damping is achieved by selecting an appropriate vibration isolator. Vibration dampers causes the oscillation in a solid body to decay to zero amplitude by diverting the energy from vibration to other sinks. Damping helps to minimize the duration and amplitude of external vibrations [17].

The first step in selecting a vibration isolator is determining the severity of environment in which the instrument is going to be used and the severity of the application. These two factors will determine the level of isolation required for the optics bench. Liquid chromatography instruments are usually operated in lab environments so the external vibration disturbances are typically in the range of 4-100 Hz. The major sources of vibration for the optics bench will be cooling fans in the detector module, motors driving needle drive mechanism, and pumps and motors in sample manager. Considering the rated speed of fans and motors which is in the range of 1500-3000 rpm, the excitation frequencies will be in the range of 25-100Hz. Therefore, all frequencies above 25 Hz must be isolated by using vibration isolators. Any excitation frequency below 25 Hz range will not have any significant effect in the performance of the detector system. While calculating the correct specifications of the vibration isolators the lowest disturbing frequency is considered. This is because if the lowest frequency is isolated, then all other higher frequencies will also be isolated. The theory behind vibration isolation is discussed in Section 3.6. The calculations for finding the right vibration isolator for the optics bench system are discussed below.

The Mass W of the optics bench assembly as obtained from the Solidworks CAD model is 3.086 kg. Assuming center of gravity of the optics bench assembly is centrally located in the horizontal plane, load W_L per mounting point is given by Equation 18.

$$W_L = \frac{W}{4} \tag{18}$$

As discussed in Section 3.6, for effective isolation of the optics bench from vibrations disturbances, the maximum isolator natural frequency f_n is given by Equation 19, where f_d is the minimum disturbing frequency.

$$f_n = \frac{f_d}{\sqrt{2}} \tag{19}$$

The static deflection Δ_s for this natural frequency is given by Equation 21, where g is the acceleration due to gravity.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{g}{\Delta_s}} \tag{20}$$

$$\Delta_s = \frac{g}{(2\pi f_n)^2} \tag{21}$$

The required spring rate K for the isolator at the mounting point is given by Equation 22.

$$K = \frac{Load/mount\ (W)}{Deflection\ \Delta_s} \tag{22}$$

Table 6 shows the calculated values of f_d, f_n, Δs and K for the vibration isolator that would provide the desired level of isolation.

Table 6: Selection of vibration isolator

Load per mounting point W_L (kg)	External Disturbance Frequency f_d (Hz)	Maximum Isolator Natural Frequency f_n (Hz)	Static Deflection Δ_s (mm)	Isolator spring rate K (kg/mm)
0.772	25	17.677	0.8	0.965

Isolators that have f_n lower than 17.677 Hz will isolate the optics bench assembly from external vibration disturbances. Many vibration isolators matching the specifications shown in Table 6 are available online. Bubble mounts from Tech Products as shown in Figure 17, have a natural frequency of 8Hz. It is made of neoprene which is chemically resistant to most solvents and each mount can take up to 2 kg of load [18]. Also the dimensions of the isolator are compatible with the dimensions of the optics bench mounting foot.

Figure 17: Low frequency bubble mount vibration isolator [18]

Transmissibility T of the selected isolators is given by Equation 23.

$$T = \left| \frac{1}{1 - \left(\frac{f_d}{f_n}\right)^2} \right| \tag{23}$$

Table 7 shows that the selected vibration isolators will provide 88.59% isolation to the optics bench.

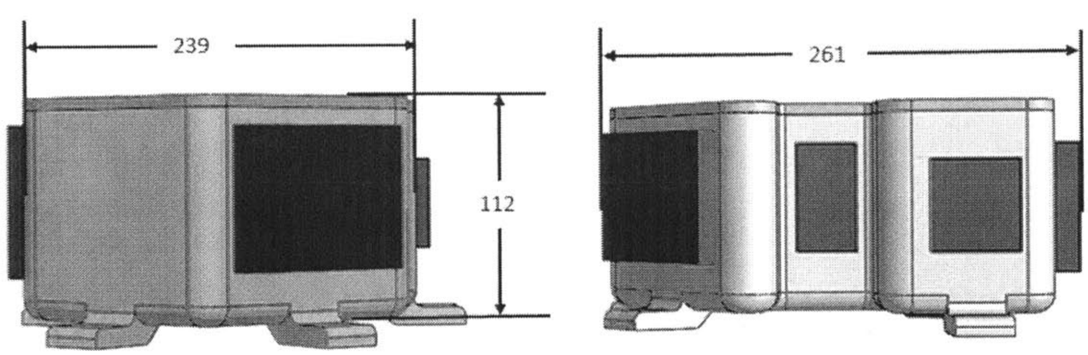
Table 7: Transmissibility of vibration isolator

Natural frequency of vibration isolator (Hz)	Transmissibility	Isolation (%)
8	0.11408	88.59

4.7.4 Thermal Analysis

4.7.4.1 Calculation of Natural Convection Heat Transfer Coefficient

Before conducting thermal analysis, the natural convection heat transfer coefficient must be approximated. For calculation simplification the optics bench is assumed to be a box of dimensions 239 X 112 X 261mm as shown in Figure 18. The theory behind natural heat transfer coefficient calculations is discussed by Çengel [19].



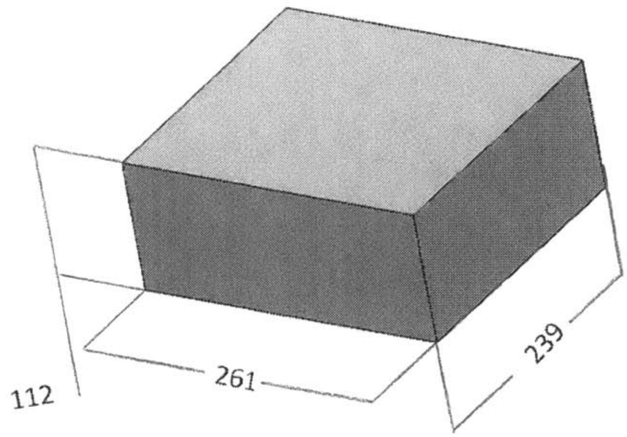


Figure 18: Maximum dimensions of optics bench assembly

The ambient room temperature is assumed to be 27°C (300K). The maximum operational temperature of the Micromirror array in DMD which acts as the major heat source in the optics bench assembly is around 60°C [20]. Thus the maximum temperature difference between the optics bench components and ambient air is ΔT = 33°C. All side faces of the box can be assumed to be 112 mm high vertical surfaces. The natural convection heat transfer coefficient h_1 for vertical faces is given by Equation 24, where ΔT is the temperature difference and L_1 is the characteristic length.

$$h_1 = 1.42\ X \left(\frac{\Delta T}{L_1}\right)^{0.25} \tag{24}$$

Table 8 shows the natural heat transfer coefficient for side faces of the optics bench, which has characteristic length of 0.112m.

Table 8: Natural heat transfer coefficient for vertical surfaces of optics bench

Characteristic Length L_1 (m)	Temperature difference ΔT (°C)	Natural heat transfer coefficient for vertical surfaces h_1 ($W/m^2 °C$)
0.112	33	5.88

Similarly the top and bottom surfaces can be assumed as rectangular horizontal surfaces. The characteristic length L_2 of the horizontal surfaces is given by Equation 25.

$$L_2 = \frac{4A}{P} \tag{25}$$

Table 9 shows the characteristic length for top and bottom surfaces, which has an area of 0.0623 m^2 and perimeter of 1m.

Table 9: Characteristic length of top/bottom surfaces of optics bench

Area of top/bottom surface A (m^2)	Perimeter of top/bottom surface P (m)	Characteristic Length L_2 (m)
0.0623	1	0.249

The natural convection heat transfer coefficient for bottom and top faces are given by Equation 26, where ΔT is the temperature difference and L_2 is the characteristic length.

$$h_2 = 1.32\,X\left(\frac{\Delta T}{L_2}\right)^{0.25} \tag{26}$$

Table 10 shows the natural heat transfer coefficient for bottom and top faces of the optics bench, which has characteristic length of 0.249m.

Table 10: Natural heat transfer coefficient for horizontal surfaces of the optics bench

Characteristic Length L (m)	Temperature difference ΔT (°C)	Natural heat transfer coefficient for horizontal surfaces h_2 ($W/m^2 {}^\circ C$)
0.249	33	4.48

The above values of the coefficient of natural convention are used in the thermal analysis in Solidworks.

4.7.4.2 Thermal Heat Sources in the Optics Bench

The proposed design of the UV-LED detector has a maximum of 11 LEDs. Now each UV-LED has a rated power of 1mW. The light from LEDs is transmitted to the light slit at the optics bench through optical fibers. Gillund [2] describes the individual efficiencies of the optical components. The amount of heat energy dissipated from the individual optical components can be calculated from those efficiency values. DMD is the most significant heat source in the optics bench assembly. The maximum heat power output from the DMD arrays is 1.1W [20]. The major heat sources in optics bench are depicted in Figure 19.

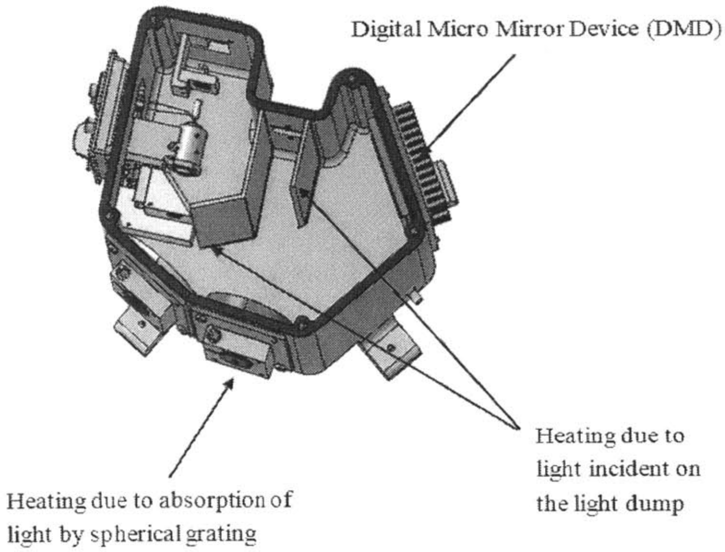


Figure 19: Thermal heat sources in the optics bench assembly

4.7.4.3 Steady State Thermal Analysis

The result of the steady state thermal analysis is shown in Figure 20. The result indicates that the maximum temperature gradient in the bench does not exceed 0.388K. Since aluminum A356 has coefficient of thermal expansion of 21.4 x 10^{-6} m/mK and the maximum linear dimension of the optics bench is around 261mm, a temperature difference of less than or equal to 0.388K will lead to differential expansion of less than or equal to 2.167x 10^{-6} m.

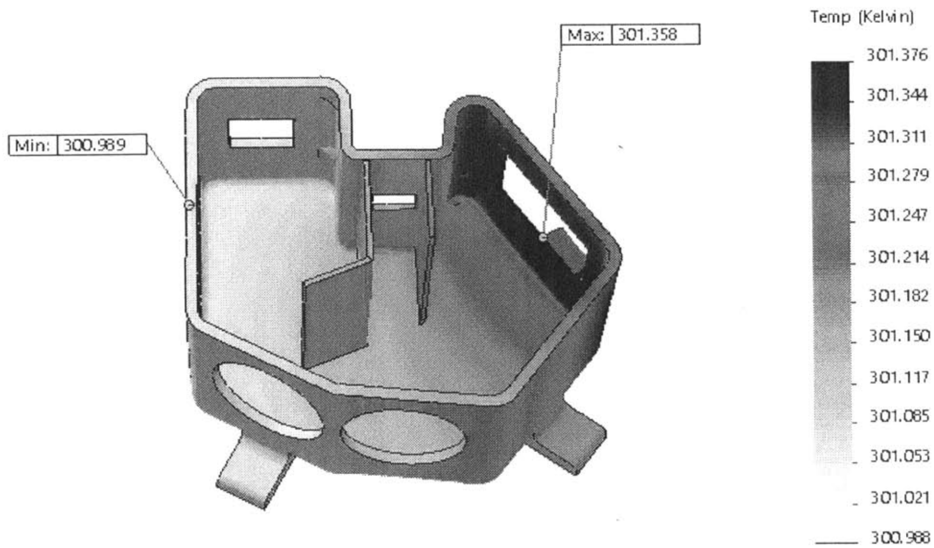


Figure 20: Thermal analysis of the optics bench

The above results also show that the steady state temperature of the optics bench is very close to the ambient air temperature (300K in this case). Further analysis by changing the ambient air temperature shows that the variation in the ambient temperature will lead to variation in the steady state temperature of the optics bench assembly. Therefore for the effective functioning of the detector system, it is necessary to decouple the effects of atmospheric temperature variation and maintain the temperature of the optics bench at a constant value. This can be achieved by a well-designed thermal management system.

4.7.5 Thermal Management

Optical components are extremely sensitive to thermal distortion. Since the precision required in optics bench is comparable to wavelength of UV light, even slight thermal distortion can seriously affect the proper functioning of the detector light engine. Thus a thermal management system and robust design strategies are critical in maintaining the dimensional stability of the optics bench and isolating it from ambient temperature variations. The strategies for thermal management in optics bench are:

- Material selection to reduce thermal distortion
- Assembly design considerations for thermal management
- Detector thermal management system

Thermal Management consideration during material selection

As discussed in Section 4.6, for the optics bench to have good dimensional stability and minimize distortion due to thermal gradient, a material with low coefficient of thermal expansion and high coefficient of thermal conductivity is selected. Aluminum A356 has a high value of coefficient of thermal conductivity λ (151W/mK) and not very high coefficient of thermal expansion α (21.6 $\times 10^{-6}$/K) which results in high $\frac{\lambda}{\alpha}$ ratio as compared to other metals and polymers. This makes aluminum a preferred and commonly used material for optical enclosures.

Assembly design considerations for thermal management

The optics bench assembly is designed such that all the individual components have their heat sources (DMD arrays, heat sinks, electronic circuitry and light source) outside the optics bench casing. This allows the external thermal management system to rapidly cool the components. The components such as mirrors, gratings and DMD also heat up due to impinging UV radiation, therefore they are thermally connected to the body of optics bench which in turn offer a larger surface area to be cooled by fans.

Detector thermal management system

The thermal management of detector consists of a system of strategically placed fans, heat sinks and air outlets that provides turbulent air flow inside the instrument for convection cooling. The locations of fans and air outlets are shown in the Figure 21.

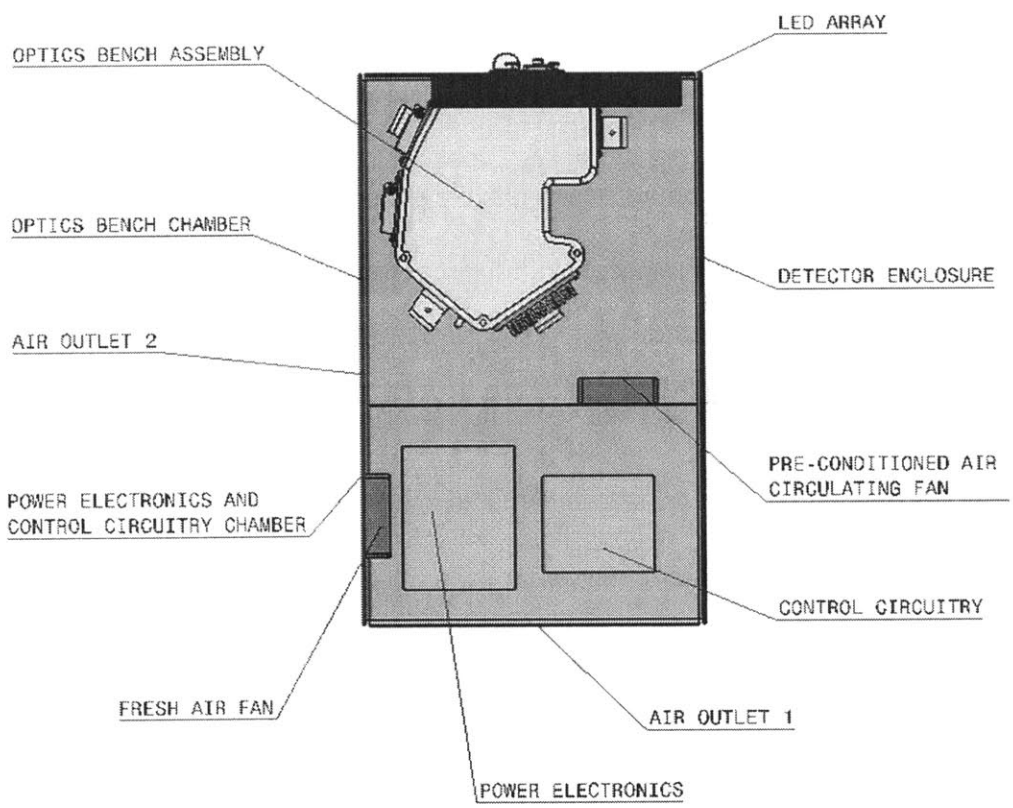


Figure 21: Thermal management system of UV-LED detector

The result of the thermal analysis as discussed in Section 4.7.4, shows that the thermal gradient in the optics bench is insignificant. The major concern is temperature variation due to variation in the ambient temperature. Therefore the thermal management system must decouple the effects of atmospheric temperature variation and maintain the temperature of the optics bench at a constant value.

The detector module is divided into two separate chambers; one for the optics bench and other for power electronics and control circuitry. There is no direct inlet of fresh air in the optics bench chamber. This allows isolating the optics bench assembly from variations in the environment. Fresh air is first preconditioned to the right temperature in the power supply and electronic circuitry chamber and then an internal fan circulates the air inside the optics bench chamber. This maintains the temperature of the chamber at a constant value. For better temperature control, a silicone strip heater can be added to the base of the optics bench. The controlled heating by strip heater and cooling by fan, will maintain the temperature of the optics bench within an optimal operating temperature range.

4.8 Manufacturing Process Selection

After the optimal wall thickness of the optics bench is determined by engineering analysis, appropriate manufacturing process is determined according to the selected material, complexity of design, tolerance requirements and cost.

- **Design Requirements**

The material selected for the optics bench is aluminum alloy A356. The geometric shape of the optics bench is decided by the optical layout of the detector system. The design of the optics bench casing and cover is shown in Figure 22. The optics bench casing is an irregular box shape structure with a plate as top cover. The weight of the optics bench casing with top cover as given by the CAD software is around 2.4 kg. The basic function of the optics bench is to precisely mount and locate optical components.

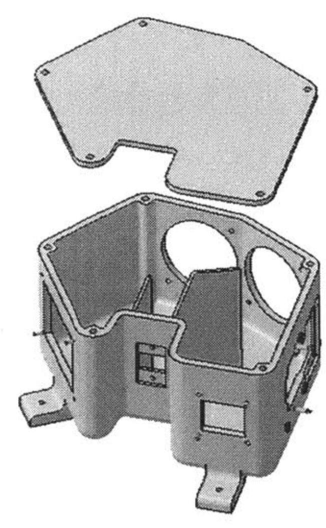


Figure 22: Optics bench casing and top cover

The dimensional accuracy required is comparable to wavelength of light. Therefore manufacturing tolerance required in the mounting holes and locating pins are in order of ±0.01mm. The annual manufacturing volume of the optics bench is expected to be around 1000 units. The design requirements and constraints for optics bench manufacturing are shown in Table 11.

Table 11: Design requirements and constraints for optics bench manufacturing

FUNCTION	Optics Bench
CONSTAINTS	Material : Aluminum A356 Shape : 3D Solid, dish shaped, flat plate top cover Mass : 2.4kg Section thickness : 6.35mm Minimum tolerance requirement : ±0.01 Annual production volume : 1000
OBJECTIVE	Minimize manufacturing cost
FREE VARIABLES	Choice of manufacturing process/processes

- **Selection Process**

Process Selection based on Material

As shown by Figure 23, aluminum can be shaped, joined and finished by a wide variety of process except that of polymer manufacturing process such as thermoforming, injection molding, blow molding, etc.

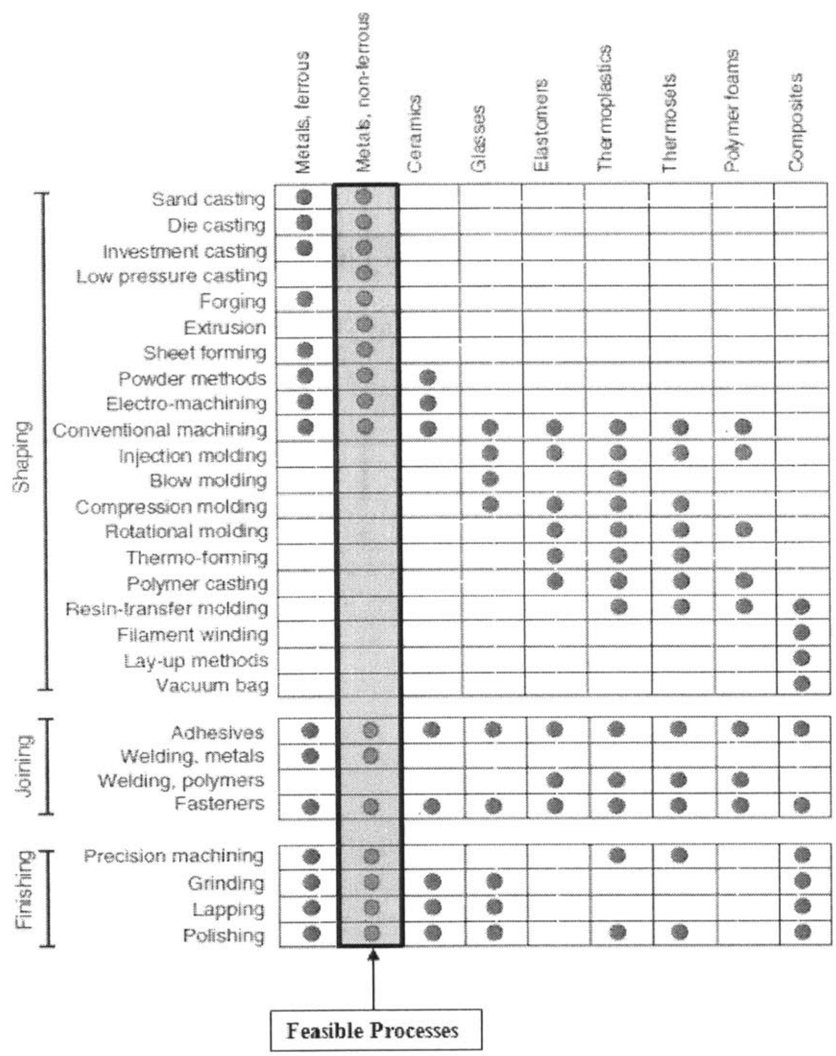


Figure 23: The process-material matrix. Manufacturing process selection based on material [3]

Process Selection based on Shape

The optics bench casing has a shape of an irregular box with a flat top cover. As shown by Figure 24, the bottom casing of the optics bench which is form of a 3D hollow solid can be manufactured by sand, die, investment or low pressure casting process. The top flat cover which is in form of a plate can be manufactured by sheet forming, electro machining or conventional machining process. Advanced manufacturing processes such as water jet, abrasive jet or laser cutting can also be used to cut the top cover profile from aluminum plates.

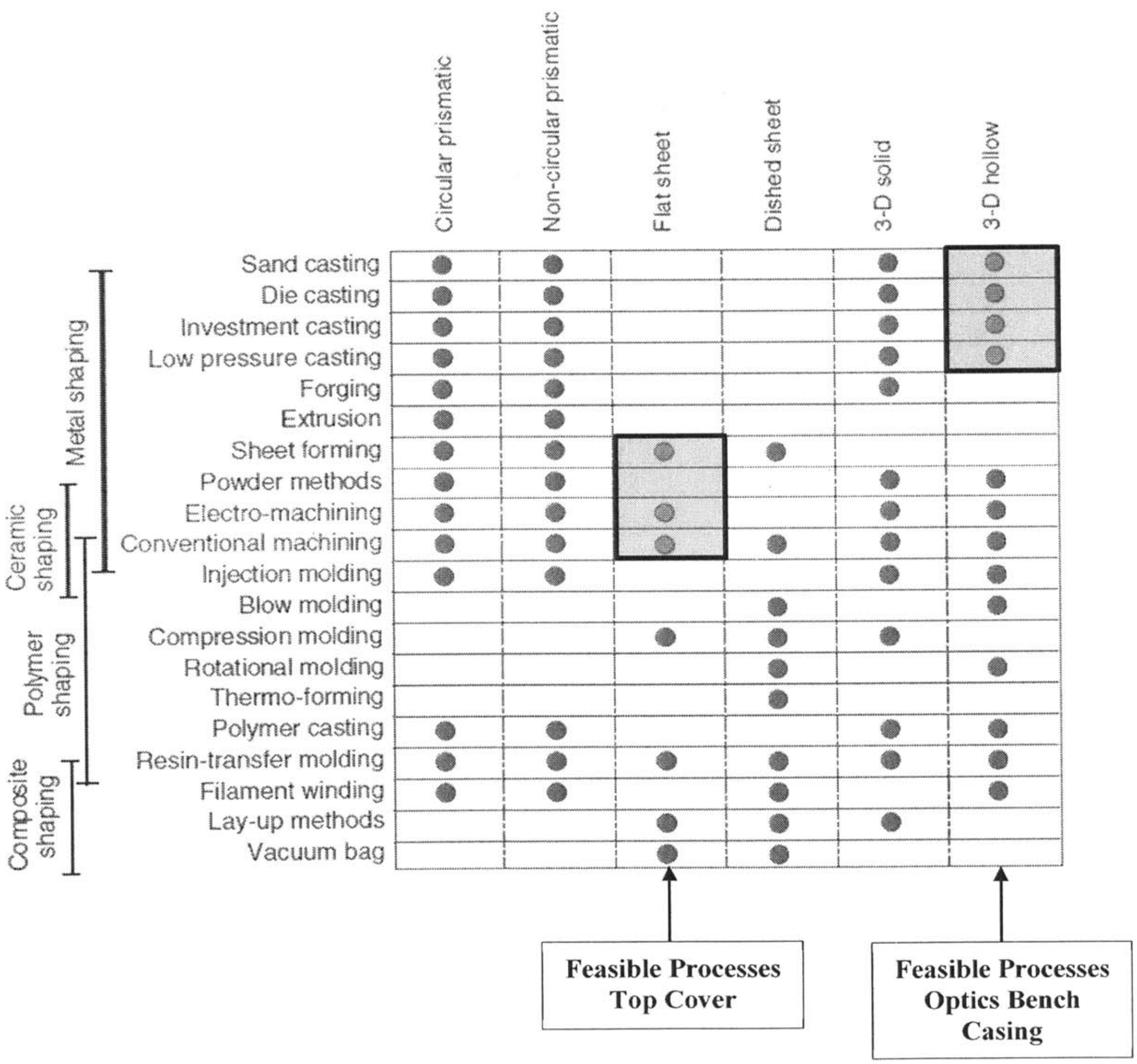


Figure 24: The process-shape matrix. Manufacturing process selection based on shape [3]

Process Selection based on Component Mass

The weight of the bottom casing of the optics bench is around 1.8kg and the weight of the top cover is 0.5kg. Given the weight, Figure 25 shows most of the metal shaping process can be used for the bottom casing and for the top cover. Adhesives, metal welding and fasteners are suitable joining processes.

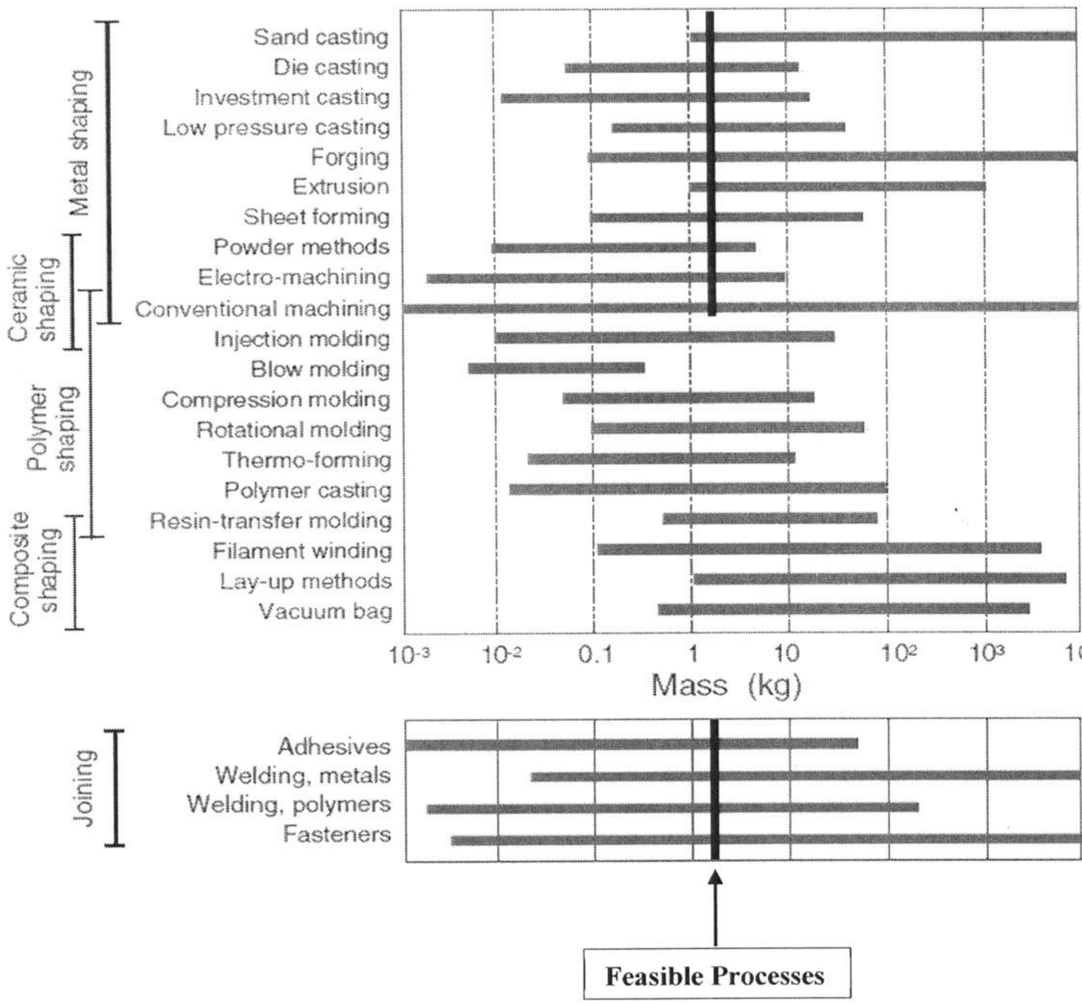


Figure 25: The process-mass range chart. Manufacturing process selection based on component mass [3]

- **Process Selection based on Section Thickness**

The optics bench casing and top cover has a maximum section thickness of 6.35 mm. In Figure 26, the vertical black line shows all the feasible processes. The sand casting process is not feasible for this level of thickness since surface tension and heat flow limit the minimum section thickness. When only considering the section thickness, all other metal shaping process are feasible for both bottom casing and the top cover of the optics bench.

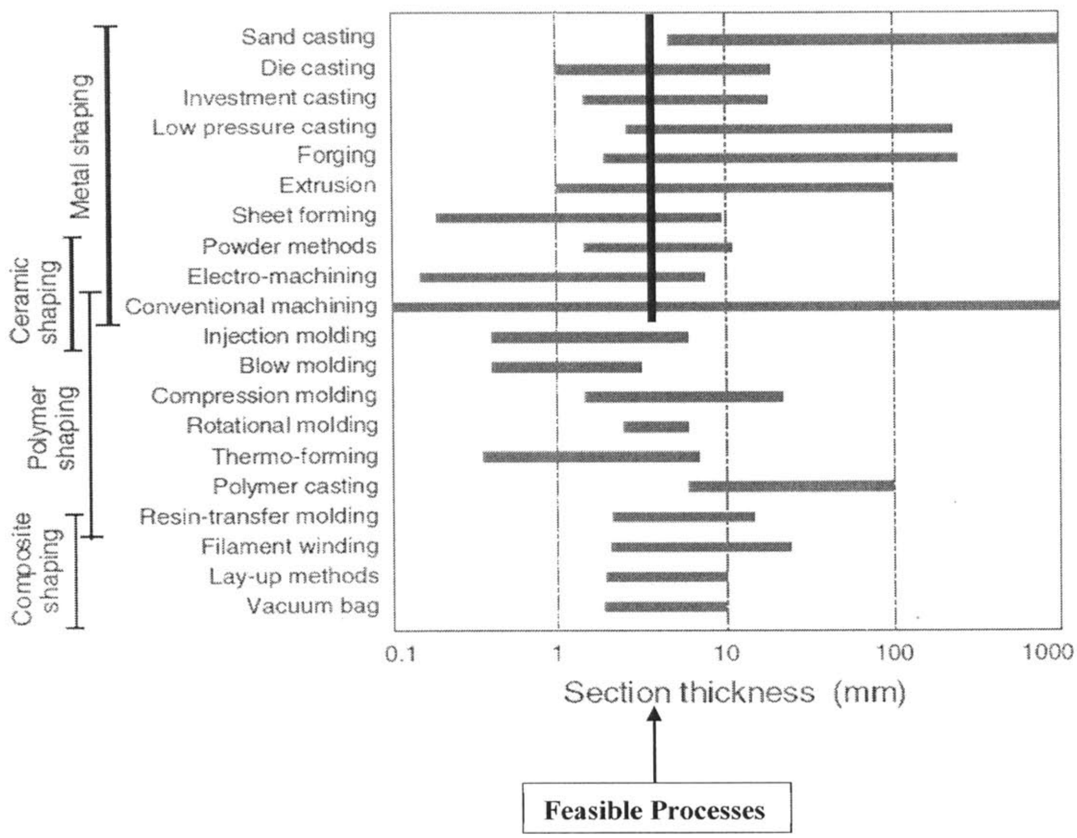


Figure 26: The process-section thickness chart. Manufacturing process selection based on component section thickness [3]

- **Process Selection based on Tolerance Requirement**

Achieving precise tolerance level of ±0.01mm is one of the key constraint in selection of manufacturing process of optics bench. As shown in Figure 27, none of the metal shaping processes are capable of achieving the required tolerance level. Such tolerances can be achieved by finishing processes such as precision machining, lapping, grinding and polishing. Therefore the manufacturing of the optics bench has to be a two-step process. In the first step a near net shape is achieved by metal shaping process such as casting or extrusion followed by precision machining of features such as surfaces, holes, slots and pins, which has tight tolerance requirements.

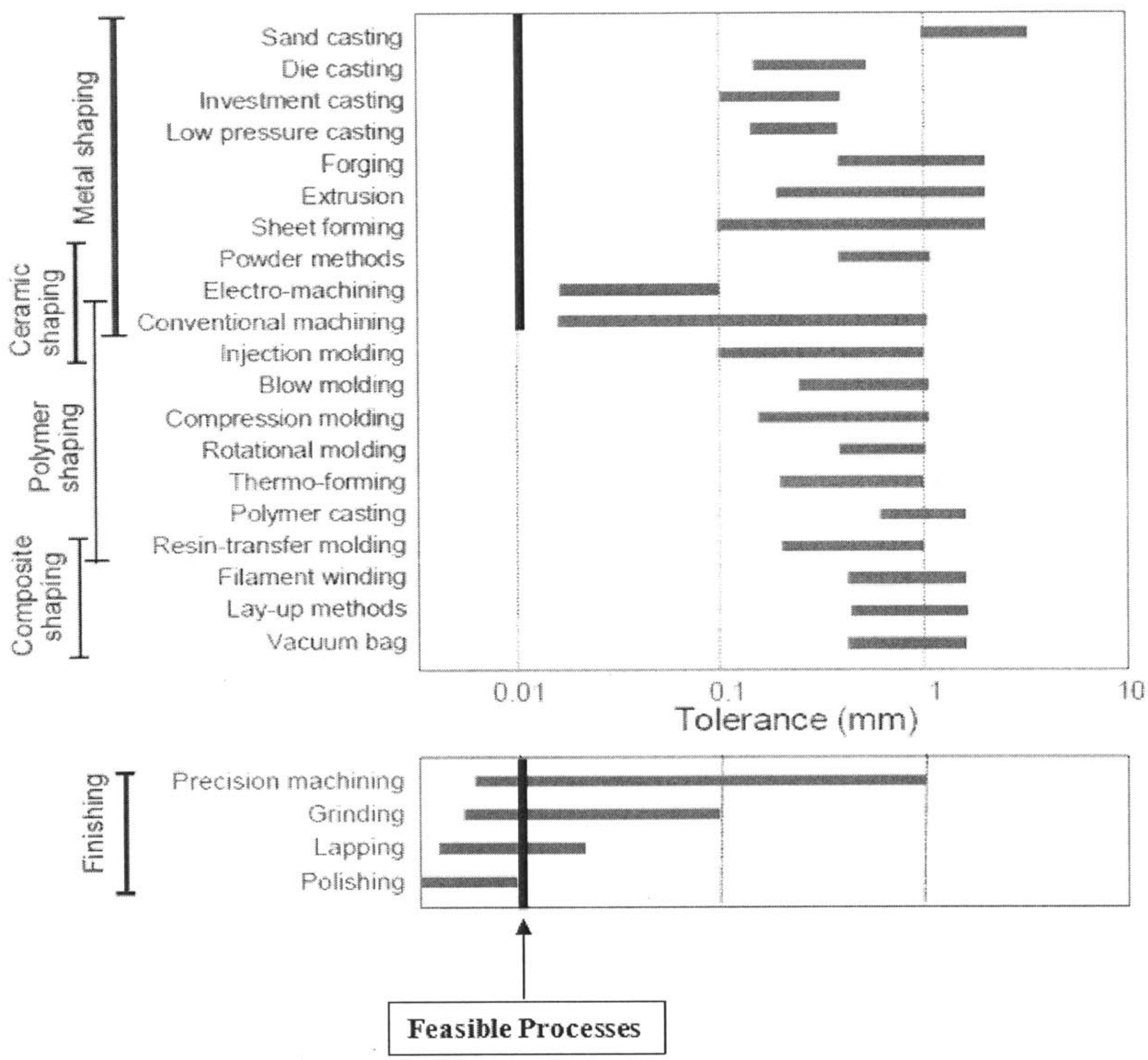


Figure 27: The process-tolerance chart. Manufacturing process selection based on tolerance requirement [3]

- **Process Selection based on Economic Batch Size and Cost**

One of the most important considerations and the final deciding criterion for manufacturing process selection is the cost. Usually, manufacturing cost depends on a number of variables such as tooling, overhead and equipment costs. The effect of all these variables can be captured by a single attribute called economic batch size [3]. It helps in deciding which is the most cost effective manufacturing process based on the number of units of the part that is to be produced annually. The annual lot size of the optics bench is expected to be around a 1000 units. As shown in Figure 28, for an economic batch size of 1000 units the manufacturing processes feasible for aluminum are sand casting, investment casting, lost foam casting, low pressure casting, forging and conventional machining process. Die casting and powder methods are not feasible manufacturing processes for a lot size of 1000 units.

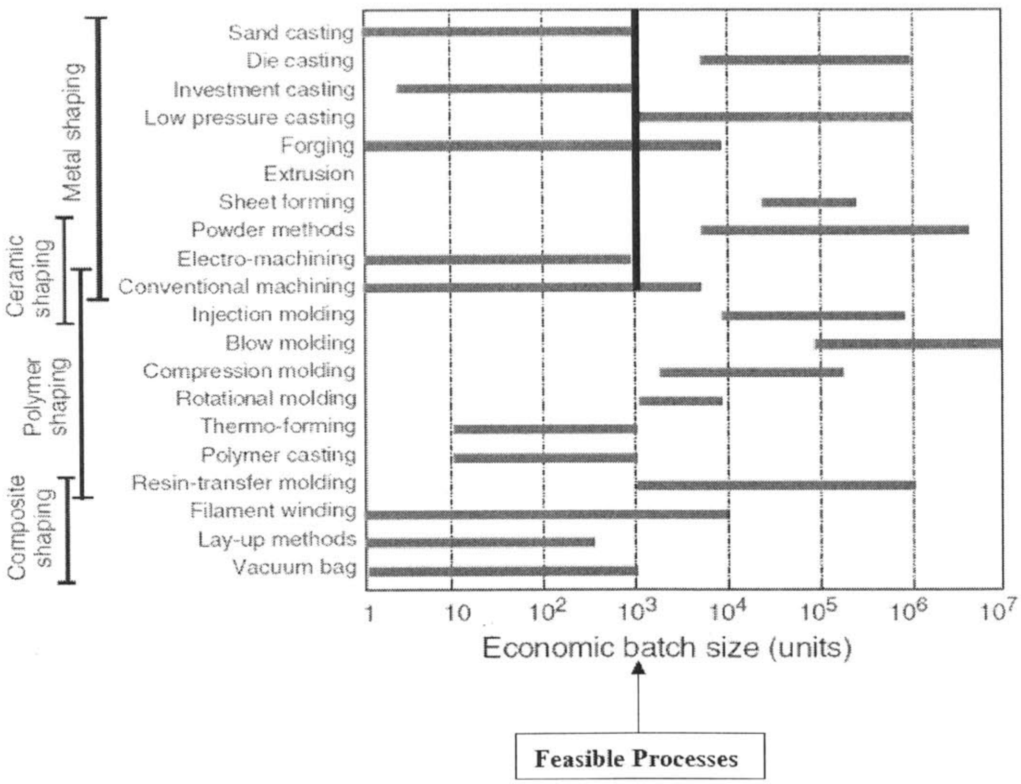


Figure 28: The economic batch size chart. Manufacturing process selection based on economic batch size [3]

- **Final selection of Manufacturing Process**

Based on the analysis from the previous sections, it can be concluded that the best manufacturing process for the bottom casing of the optics bench is casting followed by precision machining. The top cover can be manufactured from stock aluminum sheets by water-jet machining process. Since the high precision and tolerance requirements in the bottom casing of optics bench can be only met by precision machining process, the choice of casting process is dictated by cost and complexity of the part. Since the optics bench geometry is fairly complex, the best suited casting process is lost foam or investment casting process. A high level of dimensional accuracy, good surface finish and near net shapes can be achieved by these processes.

4.9 Design for Manufacturing

While designing the optics bench, all important design guidelines for lost foam casting are considered. As shown in Figure 29, in the optics bench casing design:

- Any sharp corners in the design are eliminated by fillet radius
- There are no sharp angles in the design
- Whenever possible the wall thickness is kept uniform at 6.35mm
- Sharp transitions in the cross-sectional area are avoided

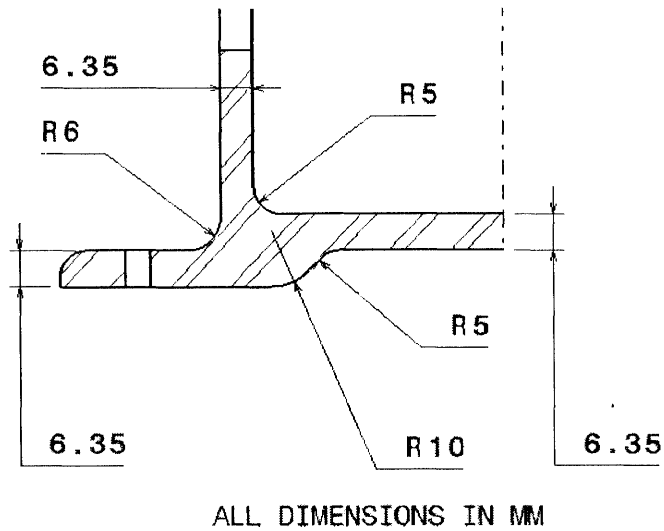


Figure 29: Cross sectional view of the optics bench

4.10 Selection of Surface Coating

Despite having some very good mechanical properties such as good thermal conductivity, good electrical conductivity, good machinability characteristics; aluminum also has some drawbacks such as it is susceptible to oxidization, abrasion and it is relatively soft when compared to other metals. Therefore parts made of aluminum need to be surface coated to mitigate or eliminate the drawbacks, avoid degradation of performance, prevent any deterioration in appearance and increase the service life of the part. In addition to these functional requirements, the coating for the optics bench should absorb any stray light and prevent it from ricocheting off surfaces. Only black colored coatings are suitable for this application because black objects are good absorber of radiation and blacker the material the more heat it radiates away [21]. Some of the important considerations while selecting an optical coating are the type of substrate material, spectral requirements, performance requirements, its effects elsewhere in the system, manufacturability, environmental degradation, maintenance and cost. The surface coatings for the optics bench should have the following characteristics:

- Corrosion resistant
- Wear resistant
- Resistant to solvents and chemicals
- High absorption and very low reflectance of a wide range of light from UV to IR
- Resistant to UV degradation
- High thermal stability in wide operating temperature range
- High thermal conductivity
- Excellent adhesion to aluminum substrate.

The places that need electrical contact or act as a reference surface for mating surfaces for high precision applications needs to be masked during the coating operation.

Some of the common methods to surface coat aluminum are

- Anodizing/Plating/Chemical films
- Painting
- Vapor disposition

Traditional black paints are not suitable for optical applications. The limitation with black paints is that they can absorb only 90% of the light incident on it [21]. Anodizing is one of the most common and popular surface coating methods, with Martin Black being the most widely used coating suitable for UV, visible and IR light attenuation applications, and is compatible with aluminum over a wide spectral range. The coating has micro protuberances and cavities that give rise to multiple reflections and scattering of radiation from surface irregularities [9]. Another optical coating that fulfils all the above functional requirements is Acktar optical black™ which uses vacuum deposition method to surface coat the aluminum substrate [22]. Some of the properties of Acktar optical black coatings which make it a suitable coating for the optics bench are

- Extremely low reflectance of light from low UV to high IR range
- Extremely thin coatings, so it can conform to the sharp edges and enhances compliance with precise part tolerance
- A wide range of thermal and vibration stability
- Highly resistant to UV degradation due to its inorganic nature

4.11 Protection against Dust, Airborne Contaminants and Humidity

Moisture and humidity have a damaging effect on the integrity and performance of optical equipment by condensing on optical surfaces or by corroding optical instruments. Other detrimental effects of water as a liquid or vapor inside optical instruments include; acceleration of stress-related fracture propagation and obstruction of transmitted or reflected radiation due to absorption or scatter. High salt content in the moisture, especially in coastal areas, can accelerate the corrosion and failure of coating on optical and structural components.

The common sources of contamination of optical surfaces are fingerprints, oil from skin, smoke and dust. The contaminants reduce performance by reducing light transmission and intensity by scattering, reflection and absorption. Another typical contaminant usually found in tropical countries with warm climate and high humidity, is growth of localized deposits and films of fungus or molds. The microscopic spores of these microorganisms is ubiquitous and can germinate and grow on even thoroughly cleaned glass surfaces. These organic contaminants degrade optical performance by introducing scatter or can permanently damage optical surfaces by etching patterns into the material [9].

There are many features in the optics bench design which isolate the optical components from dust, humidity and airborne contaminants. The isolation and protection is at two levels. One at the detector module level and other at optics bench assembly level.

First, the detector has filters of appropriate size at the fresh air inlet ports. The filters prevents large to medium size contaminants and dust particles from entering into the detector enclosure.

Second, the thermal management system is designed so the detector chamber is pressurized by blowing air into the chamber keeping dust out of the system.

Third, to counter humidity and moisture the optics bench chamber is sealed watertight by using elastomeric gaskets between the optics bench casing and the cover. As shown in Figure 30, the gasket is shaped to the profile of the opening of optics bench.

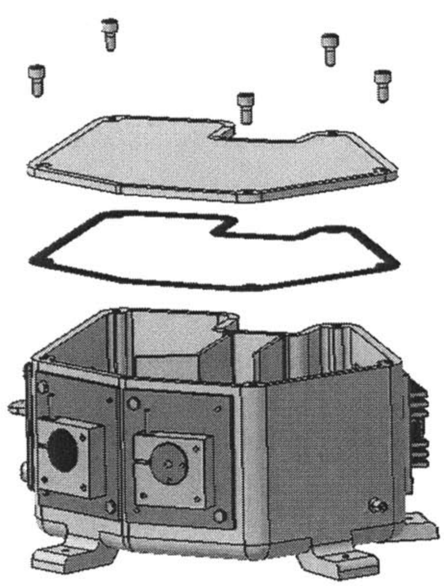


Figure 30: Sealing gasket in optics bench assembly

The gasket material must have a high chemical and UV resistance. Fluoroelastomer gaskets have high chemical inertness and outstanding UV resistance, and are suited for the above application [23].

Fourth, dry gas purging is frequently used to create very low dew points within sensitive equipment [24]. The newly built optics bench assembly must be purged of internal gaseous and fluid contaminants by using dry gas such as nitrogen or helium. The optics bench chamber must be then evacuated and backfilled with same fresh dry gas. During periodic maintenance or servicing, the optics bench chamber should be evacuated and re-pressurized with dry gas. As shown in Figure 31, the optics bench casing has a dry gas purge filler valve which is used to purge or pressurize the optics bench chamber.

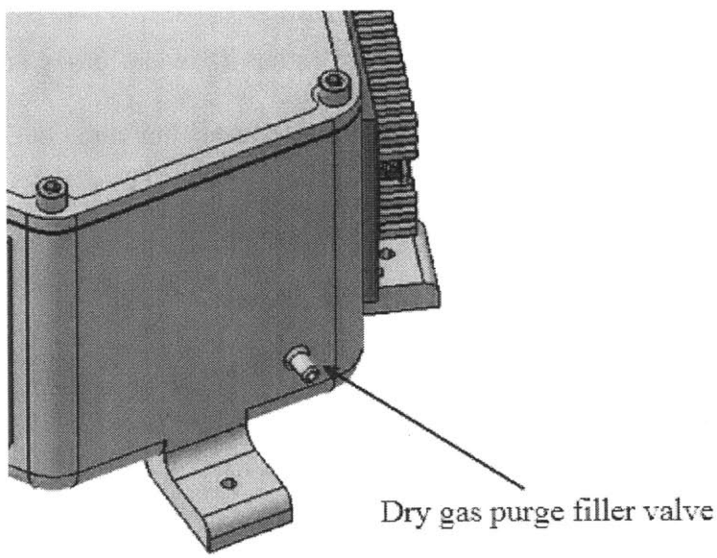


Figure 31: Dry gas purge filler valve in optics bench casing

Repeated and unnecessary cleaning of the optics bench is not recommended as cleaning unavoidably degrades the thin film coatings on optical instruments. When it is cleaned, only approved procedures, materials and solvents compatible with optical instruments must be used.

Last, the performance of the instrument will always be superior in a temperature controlled and stable environment. Therefore, the end users should be encouraged to operate the instrument in lab environment with temperature and humidity controlled by HVAC systems for better performance and consistent results.

4.12 Error Budgeting

Error budgeting is the practice of assigning permissible error to various sources on the basis of functionality, feasibility and cost. It is useful for predicting the accuracy and repeatability of the optical instruments and determines the appropriate tolerances that must be specified on the optics bench to provide adequate performance. In the optics bench assembly, the single most important measure of performance is the resolution. The major sources of error in the optics bench assembly which affect the resolution are variations in :

- The entrance slit width (Δw_{slit})
- The entrance slit and the grating (ΔL_{α})
- The distance between the DMD and the grating (ΔL_H)
- The angular alignment between the DMD and the spectral plane of the grating ($\Delta \theta_{DMD}$)

The optical layout depicting the distances L_{α} andL_H, and the orientation of DMD with respect to the spectral plane of grating, is shown in Figure 32.

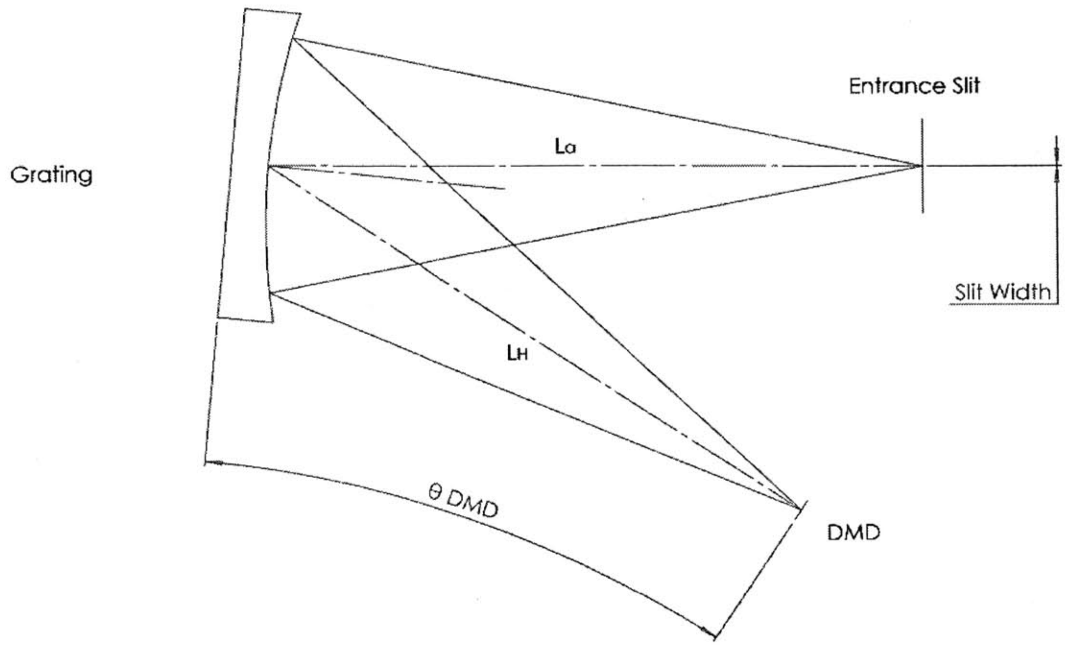


Figure 32: Schematic showing key dimensions for error budget analysis

The variation in slit width is wholly the result of manufacturing variability. Variation in distance between the entrance slit and grating and between the DMD and grating could be caused by manufacturing variability, thermal expansion and vibration disturbances. The vibration induced error is minimized by the use of vibration isolators as described in Section 4.7.3, and is insignificant compared to the errors due to manufacturing variability and thermal expansion. Therefore it is not considered in the error budget. The angular misalignment of the DMD can mainly be attributed to the manufacturing variability. Equations 27-30 give expressions for each of these variations in terms of the physical sources of the error.

The maximum variation in the slit width Δw_{slit} and its relation with the bilateral manufacturing tolerance t_{slit} is given by Equation 27.

$$\Delta w_{slit} = t_{slit} \tag{27}$$

The maximum variation in the angular alignment between the DMD and the spectral plane of the grating $\Delta\theta_{DMD}$ and its relation with the bilateral angular manufacturing tolerance $t_{\theta\ DMD}$ is given by Equation 28.

$$\Delta\theta_{DMD} = t_{\theta\ DMD} \tag{28}$$

The maximum variation in the distance between the slit and the grating ΔL_{α}, and its relation with the bilateral manufacturing tolerance t_{α} and thermal expansion is given by Equation 29, where α_{Al} is coefficient of thermal expansion of aluminum A356 and ΔT is the maximum allowable change in the temperature of the optics bench.

$$\Delta L_{\alpha} = t_{\alpha} + L_{\alpha}\, \alpha_{Al} \Delta T \tag{29}$$

The maximum variation in the distance between the DMD and the grating ΔL_{H}, and its relation with the bilateral manufacturing tolerance t_{H} and thermal expansion is given by Equation 30.

$$\Delta L_{H} = t_{H} + L_{H}\, \alpha_{Al} \Delta T \tag{30}$$

The resolution sensitivity as discussed by Gillund [2] is given by Equation 31, where NA is the numerical aperture, d_l is the linear dispersion of the grating and L_{DMD} is the length of the DMD array.

$$\frac{\partial R}{\partial L_\alpha \, \partial L_H \, \partial \theta_{DMD} \, \partial w_{slit}} = 2\, NA\, d_l(\partial L_\alpha + \partial L_H) + \partial W_{slit} d_l + \partial \theta_{DMD}(L_{DMD}\, NA\, d_l) \tag{31}$$

Substituting expressions for the variations given in Equations 27-30 into Equation 31, we get the resolution sensitivity to manufacturing tolerances and variations in temperature, as shown in the Equation 32.

$$\frac{\partial R}{t_\alpha \, t_H \, t_{\theta\, DMD} \, t_{sw} \, \partial T} = 2\, NA\, d_l\big(t_H + t_\alpha + \alpha_{Al}\, \partial T(L_H + L_\alpha)\big) + t_{slit} d_l + t_{\theta\, DMD}(L_{DMD}\, NA\, d_l) \tag{32}$$

The values of NA, d_l, L_{DMD}, L_H and L_α are determined by the optical design of the detector as discussed by Gillund [2] and shown in Table 12.

Table 12: Numerical values of NA, d_l, L_{DMD}, L_H and L_α

NA	d_l (nm/mm)	L_H (mm)	L_α (mm)	L_{DMD} (mm)
0.21	24.3	131.45	137.1	5

The resolution of the optical system is the sum of the inherent resolution R_0, given by the micromirror pitch of the DMD, and the increase in resolution ∂R due to error, as shown in Equation 33.

$$R = R_0 + \partial R \tag{33}$$

For this optical design, the inherent resolution is 0.135nm. The objective of error budgeting is to find the optimal range of tolerances which will keep the error within specified limits. The target resolution of the optical system is 1nm. Therefore, as Equation 33 shows, ∂R must be less than or equal to 0.865nm, which is the maximum permissible increase in resolution due to errors. The sensitivity of resolution with respect to manufacturing tolerances and change in temperature is derived from Equation 32 and depicted in Figure 33.

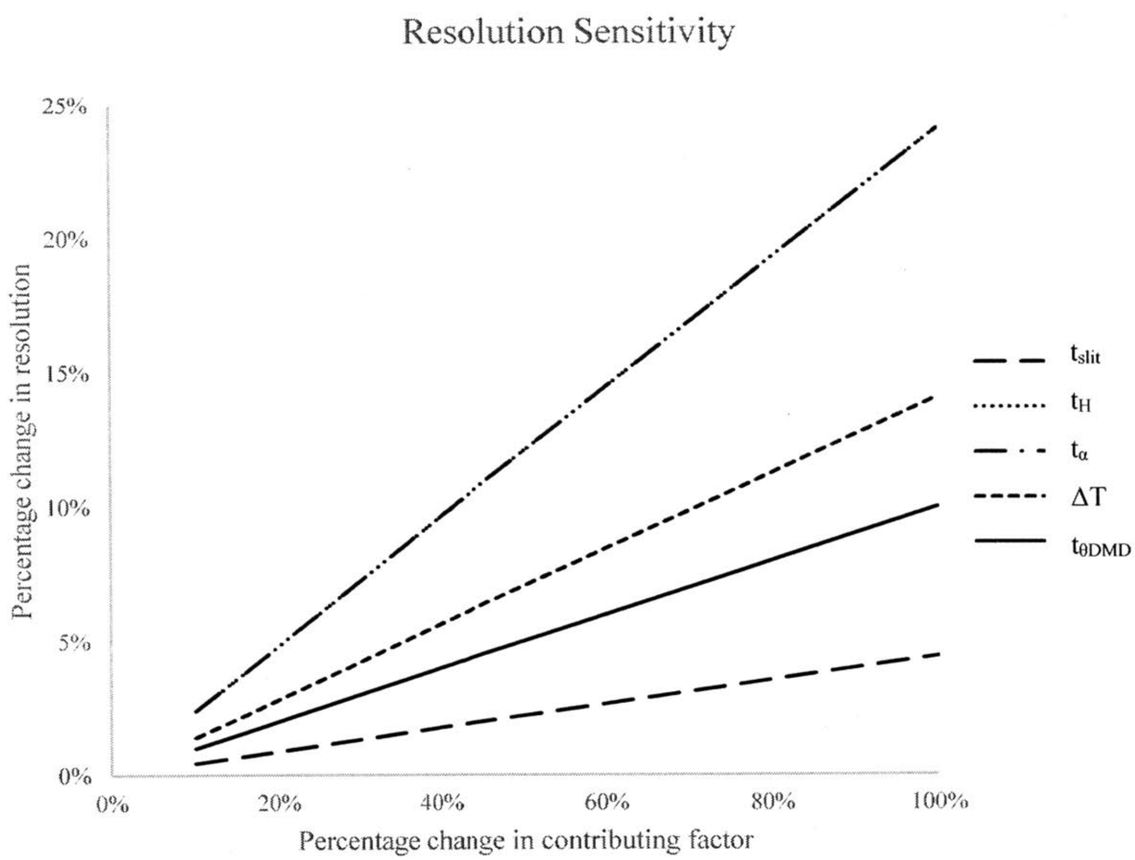


Figure 33: Resolution sensitivity

The error sources to which the resolution is not very sensitive are assigned looser tolerances to allow more flexibility in manufacturing and to reduce cost. The error sources which drastically effect the resolution even with very small changes are assigned tighter tolerance values so that the functionality of the detector is not effected.

As shown in Figure 33, the resolution is most sensitive to t_H and t_α. Both have similar effect on the resolution and thus overlap in Figure 33. Therefore, the tolerance assigned to these factors must be tight, as a large variability will severely affect the resolution. After t_H and t_α, the resolution is most sensitive is the temperature change ΔT. As a result, a thermal management system will be required to keep the temperature within the prescribed window. The resolution is not very sensitive to t_{slit} and $t_{\theta\ DMD}$, so conventional manufacturing tolerances are sufficient for these factors.

Using Equations 32 and 33, the tolerance values are budgeted keeping in view the target specifications, resolution sensitivity, the design of the optics bench, the capabilities of manufacturing processes and the expected operating conditions. Table 13 shows the error budget for the optics bench to achieve the target resolution of 1nm for the optical system of the detector.

Table 13: Error budget for the factors affecting resolution

R_o (nm)	ΔR (nm)	t_H (mm)	t_α (mm)	ΔT (K)	t_{slit} (mm)	$t_{\theta\ DMD}$ (degree)
0.135	0.835	±0.025	±0.025	±3	±0.002	±0.25

As shown in Table 13, tolerances t_H and t_α are in the range ±0.025mm. The angular misalignment of the DMD must be within ±0.25°. The entrance slit as specified by the optical design has a width of 40 microns. For this slit width a tolerance level of ±2 microns is specified by the manufacturer [25]. The temperature variation must be kept within ±3K by a robust thermal management system. A combination of precision machining and calibration can be used to achieve the desired level of resolution and minimize the error. The optics bench casing can manufactured using the lost foam investment casting process. The typical linear tolerances with lost foam investment casting are 0.005mm/mm [26]. The maximum linear dimension of optics bench is around 250mm, so the tolerances on the casted bench will be around ±1.25mm. This is well above the desired tolerance of ±0.025mm. Therefore, casting must be followed by precision machining. To accommodate post-machining steps, sufficient machining allowance must be incorporated in the design of the optics bench casting.

The tolerances achieved by machining with a 5 axis milling machine range from ±0.01mm to ±0.005mm [3][27][28]. The tolerances near the lower limit are more common and the tighter tolerances can be achieved by high precision, high cost machines. Therefore, post machining the optics bench with tolerances of ±0.025mm, can be achieved. However this level of tolerance will come at an increased cost. If cost is a constraint, tolerances in machining can be relaxed by compromising on the resolution of the optical system.

The order of operations for machining would be as follows:

- The optics bench is clamped with the top opening facing downwards.
- The four feet and their mounting holes are machined.
- The bench is fixtured to a rotary table with precision pins through the mounting holes and the mounting feet clamped against the table.
- The machining of critical surfaces and holes can be carried out with this setup on 5-axis mill.

After machining, the optics bench can be assembled. The manufacturing tolerances for angular orientation are well within the design specifications. Using an oversized DMD will allow much of the calibration to take place automatically. To achieve the required tolerances for L_H and L_α, the optical system must be manually calibrated. Therefore, calibration effort and time should be focused on the linear distances L_H and L_α as shown in Figure 34.

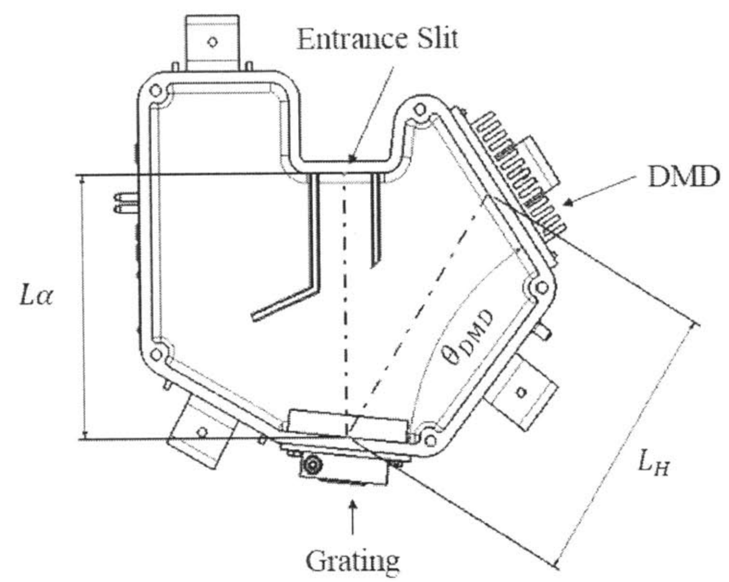


Figure 34: Schematic showing dimensions to be calibrated

The calibration mechanism is shown in Figure 35. A threaded shaft will allow the grating to move linearly and adjust the distance L_H and L_α. The angle between the axis of the grating and L_H and between axis and L_α, are small. Therefore, linear movement along the grating axis will result in 89% and 99% movement along L_H and L_α respectively. After achieving the desired resolution, the grating can be locked down to the accurate location using the clamping mechanism. The above proposals need to be tested and validated by prototyping and extensive testing.

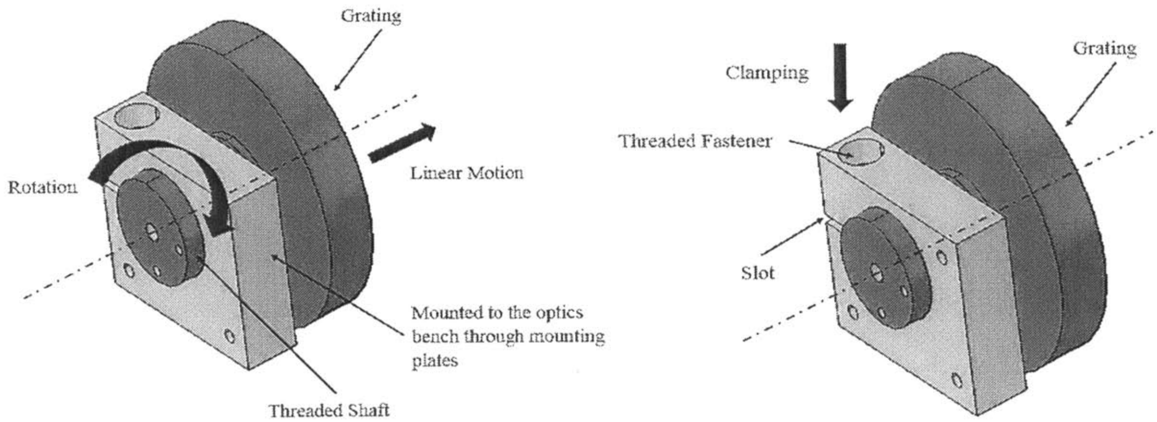


Figure 35: Calibration mechanism of the spherical grating

4.13 Prototyping

A looks-like physical prototype of the optics bench was 3D printed using a Fused Deposition Modeling (FDM) process to check any issues during assembly and service. The pictures of the prototype are shown in Figure 36. The optics bench casing, cover and mounting brackets were all 3D printed. All other off the shelf and custom made optical components such as the mirror, grating, photodiodes, flow cell, light slit and beam splitter were mounted on the printed parts. During assembly of components no major issues were observed. There was no clash of assembled components and assembly process was seamless. The slots in the optics bench had sufficient clearance to allow unobstructed assembly path for optical components for entry in the optics bench without scratch or damage. There was also unobstructed access to the tools used for assembly. But utmost care needs to be taken during the assembly process and it must be carried out in a clean room with dry environment to prevent contamination of optical components.

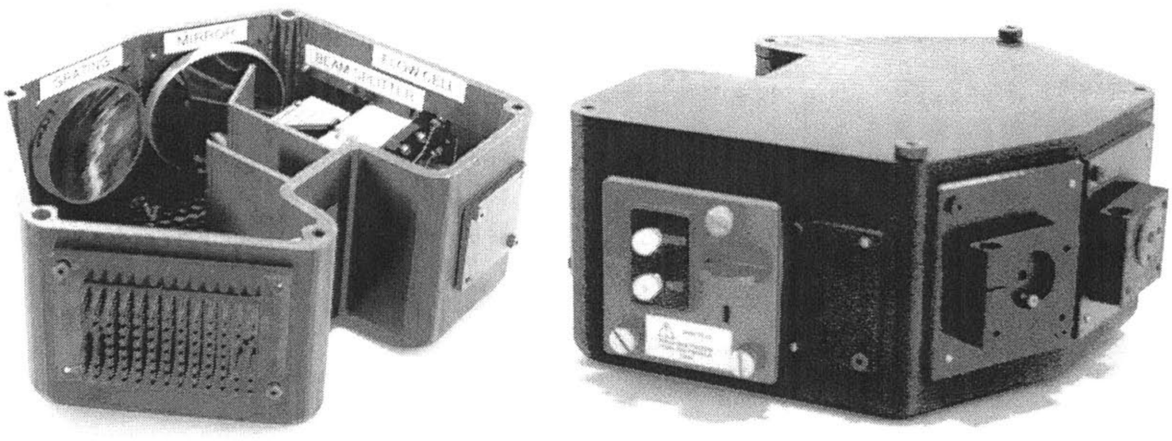


Figure 36: Prototype of the optics bench assembly

As intended in the assembly design, the optical components can be individually replaced without disassembling any other parts of the device. However there were some opportunities for improvement that can be incorporated in future design iterations:

- The orientation in which the individual components need to be assembled to the optics bench must be clearly marked to save assembly time during mass production
- Countersunk bolts can be used for better aesthetic appeal
- Wires from the electronic components such as reference and main photodiode need to be clipped together, so that they do not interfere with the working of the detector
- The optics bench casing and cover must be thoroughly cleaned before assembly of optical components. Metal chips, dust particles, oil, grease and machining coolant residues left on the optics bench after drilling, tapping and machining operations can contaminate or potentially damage the optical components. The cleaning agent used should not corrode the optical components

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

The mechanical design of the optics bench is based on the optical layout of the UV-LED based Liquid Chromatography detector. The assembly design is broken down into smaller subassemblies containing optical and structural components. The subassemblies are attached to the optics bench casing using fasteners and aligned and located using precision machined locating pins. All the subassemblies are designed to be independently replaceable to facilitate serviceability. The assembly is also designed so the thermal heat sources of the opto-electrical components are kept outside the optics bench casing.

Aluminum A356 was found to be the best suited material for optics bench application which minimizes vibration sensitivity, thermal distortion and deformation during impact loading. The material is also resistant to UV degradation, easily available and is also cost effective. After drop test and vibration analysis, it was found that a uniform wall thickness of 6.35mm (0.25 inches) increases the stiffness and natural frequency of the optics bench far above the disturbing frequencies and minimizes the stress during drop test. The weight of the assembly falls under acceptable limits. To isolate the assembly from vibration disturbances and protect the optical components during shock loading, vibration and shock mounts were incorporated in the assembly. Thermal analysis showed that the thermal gradient in the optics bench due heat generated by opto-electrical devices and radiation absorption is not very significant. But it was found that the optics bench temperature is sensitive to variation in the ambient temperature and thus a thermal management system is needed to decouple the effects of environmental temperature variation and maintain the temperature of the optics bench at a constant operating temperature. Based on the selected material, complexity of design and functional requirements, lost foam casting or investment casting followed by precision machining and water jet cutting of aluminum plate was found to be the best suited manufacturing process for both the optics bench bottom casing and top cover. Coating the optics bench with Martin black dye anodized coating or vacuum deposited coating with Acktar optical black™ is necessary to prevent corrosion and wear, and also to absorb stray UV radiation. Features such as sealing the bench watertight using fluoroelastomer gaskets and dry gas purging to protect the optical components from contaminants, dust and moisture, were also incorporated in the design.

A great deal of additional work needs to be done to fully test the functionality and validate the design.

First, working prototypes needs to be manufactured and tested in actual working environments. Any further issues with manufacturability, assembly, serviceability and quality must be identified and addressed in future design iterations.

Second, the complete detector system needs to be designed. This includes design of the detector enclosure, detailed design of the thermal management system, and design of the power electronics and control circuitry. Standardization and backward compatibility must be the focus of the design if the UV-LED detector is going to be an upgrade to the current LC systems.

Extensive testing and validation needs to done before the UV-LED detector system can be market worthy and be approved for mass production.

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