OPTI 521

OPTOMECHANICAL DESIGN

Tutorial: Overview of the Optical and Optomechanical Design Process

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I. Introduction

A wise mentor told me as I was leaving for grad school, “You write your dissertation one sentence at a time,” meaning that while a dissertation seems like a colossal task, if one breaks it up into a series of small tasks, writing a dissertation becomes more manageable. Designing an optical system is much the same; from the outside it appears to be an overwhelming task, but when broken up into its logical parts, the optical design becomes more straightforward. The art of creating a general design, grouping design parts, and working with each part until the system as whole is finished is a process that becomes easier with experience. Understanding the design process is vital in creating successful designs. The purpose of this tutorial is to illustrate the optical design process with special emphasis given to optomechanical design. Most of the basis for the material in this tutorial is a combination of the design recommendations given in Yoder’s and O’Shea’s books.

II. Objectives

The first step in any design is defining why the design needs to be done. There are many reasons why new things are designed, besides the obvious desire to make money. Typically, new designs are intended to fill a hole in the market, to create a device that performs better, or to create a design that performs as well for less money.

These statements are obvious. However, getting from an idea for a new, better optical system to the specifications needed to flesh out the idea is not obvious. Appendix A provides a list of optical and optomechanical specifications to be considered when defining a list of specifications. Note, while this list is long, many of the specifications will not become issues a given design.

Once a list of specifications has been complied, it is important to assess which specifications or aspects of the design are more important. Is the design for the lenses of a disposable camera, where cost and ease of large scale manufacturability is more important than diffraction limited performance? Or, is the design for a space telescope, where high performance and high cost is expected? It is helpful to know from the beginning in what direction trade-offs are going to be made.

O’Shea brings up an important point when considering whether or not to design a device, “Beware of the excellent, unacceptable product. There are some areas where a good idea is not accepted because those who design the device do not understand the attitude and the practices within the field.” For example, if the external design and procedures for use of a new endoscope design are too different from the current accepted devices, the endoscope will not be accepted by the medical community unless its performance is substantial better. However, if a new design can be housed and used in a similar way as the current endoscopes, there is a much better chance that the new product will be accepted. Thus, research into current designs and practices is an important part of the design process.

III. Literature Search

A literature search is good way of both assessing what designs already exist and getting ideas for a more specific design of a new system, as well as finding out road blocks that other designers ran into. Literature can be found in a number of sources, including books, peer reviewed journals, and technical reviews. These can be accessed through the Optical Science Library or the Science and Engineering Library. Patents can also be a good source of information, although it is obviously important to avoid patent infringement. Additionally, whatever research group you are working with often has a library of previous designs that can be useful starting points. As the literature search draws to a close, it is important to evaluate the differences between your proposed design and the design of others. As O'Shea points out, it is also important to figure out, "Why hasn't this been done before?"

IV. Preliminary Design

The first step of the preliminary design is to do a thin lens design to rough out the design, determine focal lengths, etc., which is then followed by a thick lens design. Once the thick lens design is completed most of the physical requirements of the optical components have been found and the optomechanical design can really begin to pick up speed. At this step element mounting, material and geometries, and other optomechanical topics of this class are evaluated, and an optomechanical system is designed. While optomechanical design is being created, it is important to keep in mind how the mounts will be manufactured and the effect of that process on the performance of the system. In many cases, time can be saved by starting a dialogue with the shop or company who may be manufacturing the system. They can answer questions about the margins of error on their manufacturing techniques, timetables, and material availability. Also, talking to the shop while still in the design mode can help you understand how they verify the performance of the part and if more testing is required by you to verify that component's performance. It is also good to keep in mind that not all parts need to be specially made. In some cases pre-made components can be used with little or no reduction in performance and a significant reduction in price. Once the optical and optomechanical designs are done, a cost analysis can be started. Additionally, Yoder gives a good flowchart of questions to verify the design. [see Fig. 4.1]

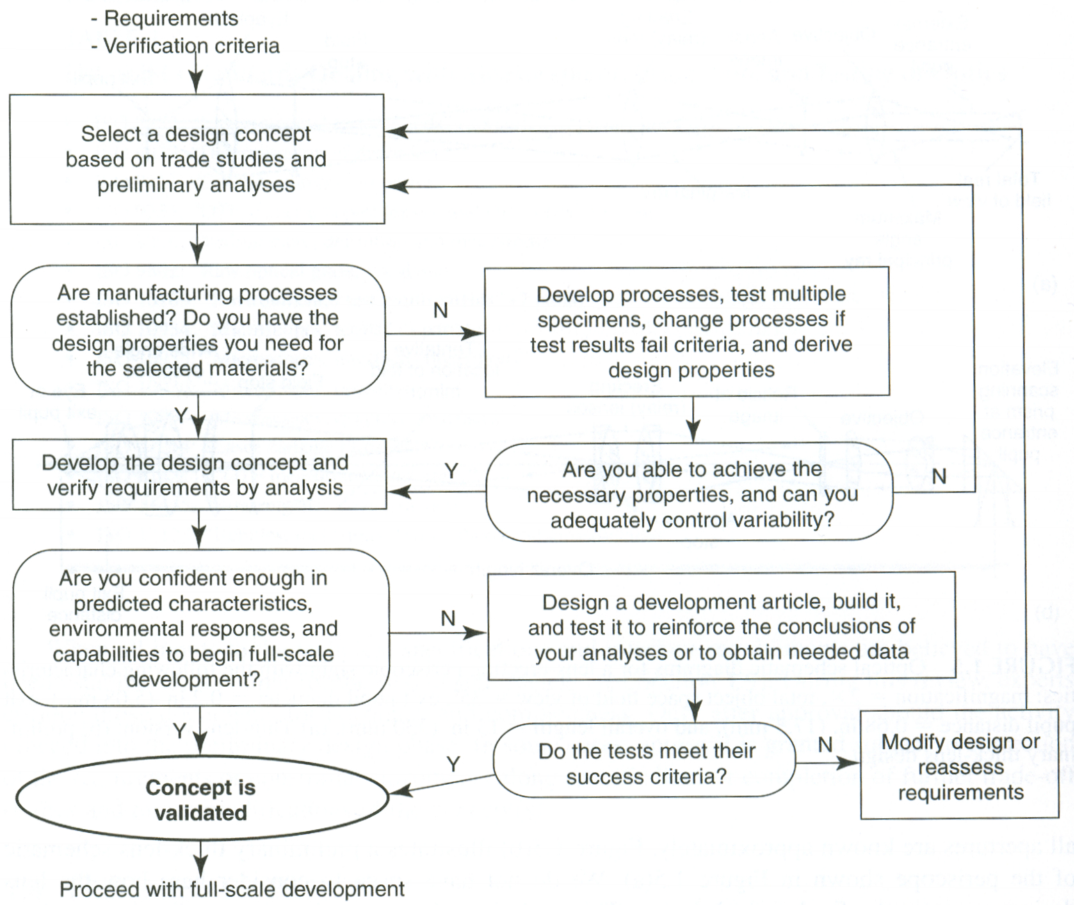

Figure 4.1 - Flowchart for Verifying Preliminary Design.

V. Evaluation and Modeling of Design

The next step after creating a design is trying to break it, or at least, finding the circumstances under which the design would fail. These circumstances might include thermal, vibrational, or shock effects. The Vukobratovich notes provided with this class contain a number of equations that can be used to evaluate these circumstances. In the event that the design does fail, either different materials needed to be chosen or the preliminary design needs to be re-analyzed. In some extreme cases the specifications for the system may need to be re-evaluated. For some simple systems it may be possible to move onto Tolerancing. For additional modeling Finite Element Analysis (FEA) could be used. The details of FEA are not the topic of this tutorial; however, in general FEA is a method of assessing the structural stability of an optomechanical system by dividing the elements of the system up into small pieces. Then the stress and strains from various environmental conditions are evaluated for each element.

VI. Tolerancing

After modeling and analysis have been done and there is reasonable confidence in the design geometries and material choices, tolerance can begin. Tolerancing is essentially figuring out how far the manufacturing of the system elements and the operational conditions can stray before the level of system performance drops below a predetermined, acceptable level. The process of tolerancing was covered well in this class, so only an abbreviated discussion will be given here. The first step of tolerancing is defining starting tolerances, or allowable manufacturing errors. Then the effect of these standards on merit function of the system is calculated. Once the effects of the different degrees of freedom have been calculated, the effects are rot-sum-squared to estimate the performance. Often the performance is not acceptable and the tolerances need to be tighten and the process repeated. Figure 6.1 shows a flowchart for the tolerancing processing. Another method of analyzing tolerances is to use a Monte Carlo simulation. In this simulation the degrees of freedom are randomly varied to simulate the randomness of manufacturing.

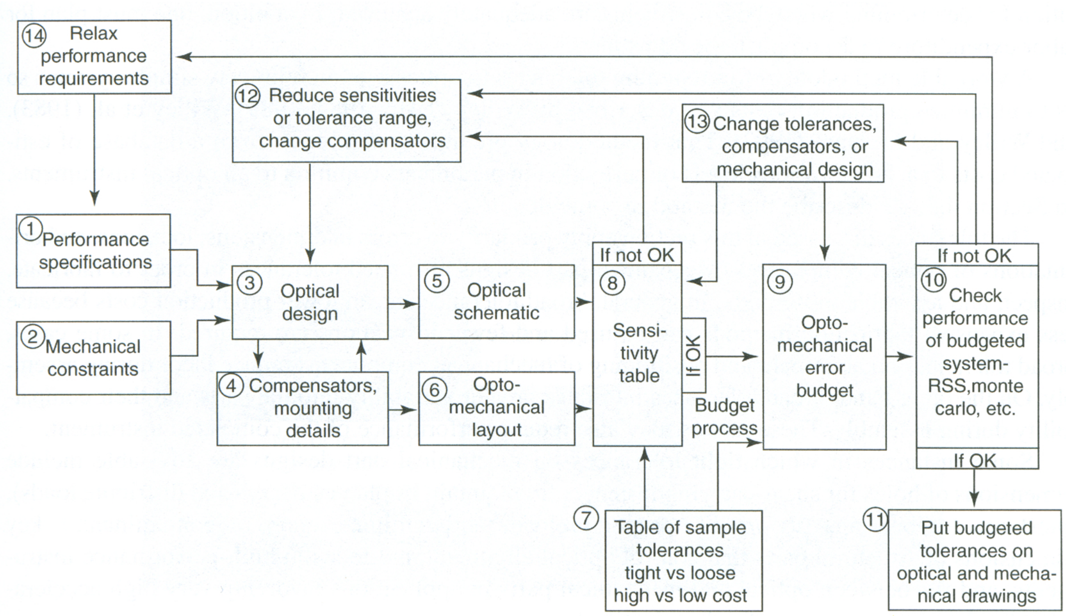

Figure 6.1 - Flowchart for Tolerancing Process.

VII. Experimental Verification

Another important step of the design process is to physically model the system. Whether it is building a prototype or breadboarding, the performance of the design can be estimated. It is important to model the system as closely as possible including the materials used, the way the elements are manufactured, and the operational conditions. Once the designer is confident through modeling and tolerancing, the design can be finalizing. At this stage it is useful to double check the design and review past documentation about the design choices that where made, after which the design can be sent off for manufacturing.

VIII. End Product Verification

After the final system is built, it is important to verify that it meets the design requirements. Figure 8.1 from Yoder provides a good flowchart for final testing. If for some reason the design does not meet the requirements it is possible to fix the system by experimentation or by measuring the characteristics of all the components, inputting them into the optical design, and adjusting spacings or adding a correcting element. However, any adjustments made at this point usually take time and are quite costly. Yoder also mentions that tracking the performance and condition of the system over the time of the device's use can provide an insight into the problems that were unseen and the validity of assumptions made during the design process.

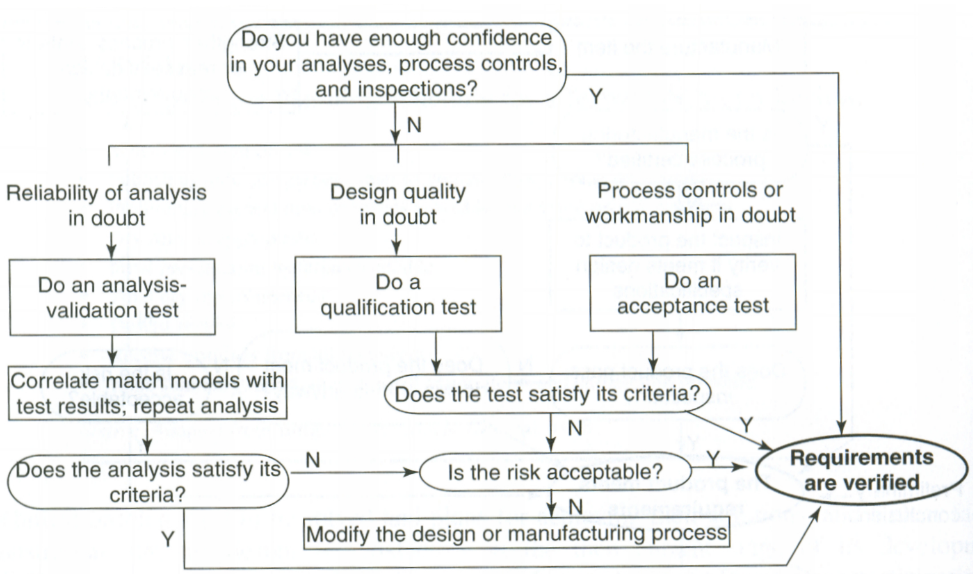

Figure 8.1 – Flowchart for Final Testing.

IX. Important Final Notes

Below are some useful suggestions for general designing.

- ❖ Separability: It is important, and difficult, to separate yourself from your design. Without doing so, it is difficult to accept constructive criticisms. Also, if you can not separate yourself, it is easier to become “married” to a specific design and to stubbornly push through a design that is not the best for a particular application.
- ❖ Design Reviews: While they seem tedious and a waste of time, design reviews are useful in tracking the progress of the design and assessing potential problems. The list below shows the reviews and their order recommended by Yoder.

1. Systems Requirements Review: prior to initiation of design,
2. Preliminary Design Review: following conceptual and preliminary design,
3. Critical Design Review: following detailed design,
4. First Article Configuration Review: following an initial production run.

- Documenting the Design: **This is the most important piece of advice**. It is too easy to assume that what happen on Day 1 will be easy to remember on Day 14 and what is obvious now will be just as obvious later. Documentation may seem like a waste of time now, but the time taken to document a design well is much less than the time it will take to have to figure something out again. Documenting a design can include, but is not limited to, keeping track of daily progress- or issues, tracking the different phases of a design, summarizing meetings and phone conversations, writing down why a particular design decision was made, and keeping track of all results- even the bad ones. Trust me, documenting reduces headaches. ***DOCUMENT IT!***

X. References

O'Shea, Donald C., *Elements of Modern Optical Design*, John Wiley & Sons. Inc., 1985

Shannon, R.R., *The Art and Science of Optical Design*, Cambridge University Press, 1997

Yoder, Paul R., *Opto-mechanical Systems Design: Third Edition,* CRC Press, Taylor and Francis Group, 2006

Prof. Burge, "OPTI 521: Optomechanical Design Lectures", Fall 2007

Prof. Sasian, "OPTI 517: Lens Design Lectures", Fall 2007

Appendix A. Optical and Optomechanical Specifications for Consideration: Combination of Specifications from Yoder and Shannon

Focal length	Interfaces	Size, shape, and weight limitations
Field angle or field size	Optical	Moment about mounting
F/number	Mechanical	Producibility
Numerical aperture	Electrical	Manufacturability
Wavelength and spectral range	Electrical requirements and restrictions	Manufacturing processes
Magnification	Power consumption	Mounting procedures
Magnification range	Frequency	Mounting interfaces
Image orientation	Phase	Mechanical interface with instrument
Type of lens	Grounding	Surface finish, cosmetics
Back focus	Materials	Beam parameters
Front focus	Availability	Radiation damage
Pupil locations	Cost	Irradiance damage
Illumination	Continued supply	Maintenance and servicing provisions
Irradiance uniformity	Suitability for processing	Human-instrument interface requirements and restrictions (including safety aspects)
Vignetting	Environmental considerations	Prior experience
Transmission	Hazardous materials	Track record
Ghost images	Environment	Prior art
Distortion	Temperature range	Patentability
Variation with conjugates	Thermal stability	Patent conflict situation
Variation with spectral region	Storage conditions	Competitive situation
Folding components	Atmospheric pressure	Cost of design
Interference with optical path	Humidity	Cost of prototype
Zoom range	Vibration and shock	Cost of production
Zoom mechanization	Availability of subcontractors	Schedule and delivery time
Focus mechanization	Level of technology	Marketability
Image quality	Coatings	Interface to other products
Aberrations	Transmission	Lifetime of product
Resolution	Reflectivity	Rate of production
OTF	Absorption	Environmental hazards
MTF	Availability	Liability issues
Energy concentration	Risk	Delay to market
Effects of aperture stop	Environmental effects	Timing of disclosure
Scattered light	Detector	Integration with products
Polarization	Photographic	Customer view of product
Veiling glare	Sampling array	Styling
Light baffling	Signal to noise	Financial viability
Off-axis rejection	Dimension	Investment requirements
Field stop definition	Spectral response	Investment risk
Diffraction effects	Element size and spacing	Access to funding
Tolerances	Frequency response	
Depth of focus		
Interface with variable aperture		
Interface with autofocus system		
Image quality at various apertures		