Training of optomechanical engineers at the University of Rochester

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ABSTRACT

The University of Rochester is well known for the Institute of Optics as well as a strong Mechanical Engineering program. In recent years, there has been collaboration between the two departments on a variety of topics, including a new joint faculty position. There are new cross-listed courses in Optomechanics and Precision Engineering (Spring 2012), which are described in this paper. As yet, there is no formal specialization in Optomechanics, but many students create their own program from available courses combining optics and mechanics with other disciplines. Students have the opportunity to participate in the several research areas which cross discipline boundaries. For example, a student design team is building a 16” telescope which they hope can become the basis of an intercollegiate design contest. In addition to full semester courses, there is a summer program of short courses available to working engineers as both refresher courses or as introductory courses on new topics.

Keywords: optomechanics, training.

1.0 INTRODUCTION

Optomechanics is the merging of two disjoint fields of study, optical sciences and mechanical engineering. As optical designs strive for higher performance, they are plagued with problems which fall in the field of mechanical engineering, such as thermal distortion affecting wavefront error or vibrations affecting line-of-sight errors. Many precision mechanical systems rely on optical sensors and metrology systems to improve feedback measurements for position control. Modern optical and precision systems inherently require knowledge in both optics and mechanics, as well as aspects in signal processing, metrology, and controls. To solve these problems, mechanical engineers need additional training in the field of optics and likewise, optical engineers need additional training in mechanics. This paper provides background into the interdisciplinary training available in this area at the University of Rochester.

2.0 COURSES

Currently, there is no formal degree program in optomechanics, however many students create their own program through electives. The Bachelor of Science degree program for undergraduate mechanical engineering and optical engineering students is structured with many fixed courses so there are only a few electives available. At the Master of Science level, there is a lot of freedom to take cross-disciplinary courses. Students desiring to work in optomechanics take advantage of this freedom to create their own program of studies, combining classes in optics, mechanics, and other disciplines based on their desired career trajectory. In the future, the these courses may be structured to offer a Master of Science degree in either Mechanical Engineering or Optical Engineering with a specialization in optomechancis. In the sections below, typical course with strong applicability to an optomechanical engineer are listed

2.1 Mechanical Engineering

Mechanical engineering courses which support topics relating to designing, qualifying, and implementing optomechanical systems are typically aligned within two areas: structural analysis and material properties. For structural analysis, an optomechanical engineer must be capable of prescribing and predicting the motion of complex systems. This is often the case for large telescopes which have a network of supports for mutli-segmented mirrors and metrology systems such as those in lithography tools which measure and image with high accuracy. Here, optical mounting techniques and accounting for error sources within a system is a crucial aspect to overall system performance. Classes which support the fundamental background for topics include Applied Vibrations, Dynamical Systems, and Mechanical Design.

When optical systems are a scaled down and a more fundamental approach is needed, material properties define the basic functionality of a material in an optomechanical system. This could be investigating the material structure, optical properties, or characterizing the thermal behavior for devising new, complex optical materials. As these challenges are scaled up, optical components need structural support and analyzing multi-material interfacing becomes a critical factor in many optomechancial systems. Crystallography and X-ray Diffraction, Mechanical Properties of Polymers, and Thermodynamics of Solids are examples of courses which support this topic.

Typical courses of interest offered by the Mechanical Engineering Department for optomechancial engineers are:
- Applied Vibrations
- Finite Elements
- Mechanical Properties of Polymers
- Crystallography and X-Ray Diffraction
- Mechanical Design I & II
- Thermodynamics of Solids

2.2 Optical Science and Optical Engineering

Mechanical engineers stepping over into optics typically need a fundamental understanding of the basics of optical systems. This includes both the "ray" and "wave" nature of light, refraction, and the wavelength/material dependency for most optical properties. Basic concepts like focusing light, interference, and diffraction are all needed as building blocks for more advanced topics. Additionally, most modern optical systems use some form of a laser and an understanding of its operation and different types is central to many systems. Courses in these areas include Geometrical and Instrumental Optics I & II, Physical Optics I& II, Lens Design, and Fundamentals of Lasers.

More advanced optics topics for optomechanical engineers include Aberrations, Interferometry, and Testing and Optical Fabrication and Testing Technology. While much advanced optical design is performed by optical engineers, optomechanical engineers need to understand aberrations and how to manufacture complex surfaces because mounting stresses can augment inherent aberrations or create new aberrations. In addition to understanding the theory, optomechancial engineers must understand the metrology tools (and their concepts) for testing optical performance.

Typical courses of interest offered by the Institute of Optics for optomechancial engineers are:
- Geometrical and Instrumental Optics I & II
- Lens Design
- Aberrations, Interferometry, and Testing
- Physical Optics I & II
- Optical Fabrication and Testing Technology
- Fundamentals of Lasers

2.3 Cross-listed Courses

There is currently one cross-listed course, Optomechanics, which directly addresses analyzing optomechanical systems. Starting spring 2012, another cross-listed course, Precision Engineering, will be taught which addresses metrology concepts and designing precision systems which often include complex optical subsystems and components. Optomechanics has been taught for the last five years while Precision Engineering will be a new course next year. The content of both courses is given in the following sections.

2.4 Summer short courses

In addition to semester courses, the Institute of Optics offers a series of summer short courses every year. These allow working engineers to get a quick overview of a variety of topics. The 2.5 day long courses this year include:

- Optomechanical Analysis
- Modern Optical Engineering
- Non-imaging Optics
- Biomedical Optics
- Fundamentals of Optics
- Optical Thin Film Coating Technology
- Lasers and Optoelectronics
- Electron Microscopy

Details are available at www.optics.rochester.edu/external_programs/summer_school

3.0 OPTOMECHANICS COURSE

The Optomechanics course is cross-listed in mechanical engineering and optics as both an undergraduate and graduate course. The graduate version has a term project required. Some of the major topics in the course are:

- *Review basics for both mechanical and optical engineers.* Students entering a new field need an overview of the basics in that field. Topics include elasticity, materials, figures of merit, optics theory and terminology
- *Training on tools required for optomechanical analysis*. The analysis of mechanical disturbances on optical performance require software tools: Patran for model generation; Nastran for static, dynamics and thermal analysis; SigFit[1] for polynomial fitting, line-of-sight, thermo-optic and stress-optic analysis.
- *Optical surface distortions.* Mechanical distortions are decomposed into rigid-body motion and higher order distortions which are then fit with Zernike (and other) polynomials. Polynomial normalizations and orthogonality are addressed. Grid (interferogram) arrays are presented as an alternative approach.
- *Finite element modeling of optical components.* Techniques for modeling solid mirrors and lenses, as well as large lightweight mirrors are presented. Topics include model resolution, accuracy, quilting, symmetry, model checkout and validation.
- *Mounting of optics.* The advantage of kinematic mounts is discussed and the implementation through flexures. Adhesive bond issues are explained, including the effects of nearly incompressible materials.
- *Test supports.* Several common test supports such as airbags, V-blocks and others are reviewed. Techniques are presented for test-analysis correlation, as well as gravity backout analysis.
- *Vibration of optical systems.* This topic requires some review of basic vibrations theory, modal analysis, and random response analysis. Methods for line-of-sight calculation are presented. This allows calculation of jitter MTF effects. Vibration isolation concepts are addressed.
- *Thermoelastic analysis.* Basic heat transfer analysis is reviewed. Athermal design concepts are presented, as well as related topics of CTE variation and index change with temperature (dn/dT).
- *Stress in optics.* The difficult issues related to the strength of glass are discussed. This section also includes the analysis of stress birefringence.
- *Advanced topics.* Structural optimization of optical systems. Adaptive optics.

Homework problems address each of the major topics. All of students actually create finite element models of optical components for analysis under gravity, thermal loads and dynamic loads. After the finite element analysis, the data is processed in SigFit to fit Zernike polynomials. Students get to see the difference between global rigid body errors and higher order elastic errors. Deformation results are presented in a format directly importable to optical design codes. For a lens system, students compare the optical effects of thermal distortion, thermal-optic index change, and stress-optic index change.

This course is popular with both mechanical engineering and optics students with an overall split of about 50-50. Having that balance in class, for discussions and questions, adds to the learning experience. Both sets of students get to learn the terminology and issues of the other. This interaction should provide engineers with a better background for teamwork in future optomechanical projects. The textbook for the course is Reference 2.

4.0 PRECISION ENGINEERING COURSE

A cross-listed course in precision engineering will be offered starting in spring 2012 and covers many topics relating to precision machine design, metrology, calibration, error budgeting As part of the course, graduates students are expected to work on a project where they will either analyze an existing precision system or devise a new precision system to achieve some specified objective. The course topics are as follows:

- *Basic Metrology Concepts:* Many precision systems rely on integrating metrology directly into the system to achieve sub-micrometer or even nanometer performance. A basic understanding of metrology concepts is needed including vocabulary, national and international standards, probability distributions, and Type A/B uncertainties. In addition, concepts for production like repeatability and reproducibility are addressed.

- *Static Constraints*: Many systems rely on constraining components and sensors where there is little deformation to the component/sensor. Concepts like the number of degrees of freedom, exact constraints, over constraints, and elastic averaging are explained. Component mounting, particularly for optomechanical engineers, is crucial especially when dissimilar materials are considered. http://www.odalab-spectrum.org/Images/TitlePic.gif
- *Thermal Considerations in Instrument Design:* The driving force for many design choices in optomechanical systems depends on the thermal characteristics. Designing for thermal datums and managing thermal expansion with dissimilar materials is often critical. Additionally, concepts like material normalization to compare materials during the selection process are discussed.
- *Motion and Motion Control (Dynamic Constraints):* Once an object can be placed within a system, the next step is addressing motions of that object. This includes bearings, guideways, and motors. Also, basic concepts for floating stages and controls are presented.
- *Flexure Design:* Flexures are generally a subset of motion control but are critical components in many optomechanical systems. Flexures are often used to generate a known force based on a displacement or a linear motion without much hysteresis, Flexures can be used to limit stressed applied to optics from thermal expansion and/or can be used to guide a linear motion of a component crucial to the optomechanical system's functionality.
- *Displacement Interferometry:* Displacement interferometers are widely used in calibrating precision stages and sensors. Different configurations are discussed and the basics of signal processing interferometer signals are presented.
- *Machine Tool Metrology:* The last precision engineering concept presented is machine tool metrology, which essentially combines all of the previous topics. Straightness, roll, pitch, and yaw errors are discussed and an error stack-up in a multi-axis system is presented. This is essentially the backbone for designing many of the precision manufacturing systems where nanometer level tolerances are needed over large surfaces.

The overall goal of the Precision Engineering Course is to impart enough knowledge on to students for them to critically assess the performance of a system. Students who have completed the course should be able to design precision systems while simultaneously considering aspects from many different disciplines.

5.0 RESEARCH

In addition to course work, there is a wide variety of research at the university related to the broad field of optomechanics. Some of the topics include the following:

- Stress birefringence
- Optical materials
- Strength of glass
- Optical fabrication and polishing
- Interferometric testing

Research in the Precision Instrumentation Group heavily focuses on optomechanical research. Current research topics include high power, high frequency gas laser stabilization and fiber-based interferometry for precision and medical applications.

A unique advantage of a smaller school like the University of Rochester is the ability of undergraduate students to participate in research. Listed below are research topics in which undergrads are listed as authors or co-authors:

- Thermal shock testing of borosilicate glass
- Coolants/lubricants for optical manufacturing
- Coolant testing at high speeds
- Laser damage simulations in glasses
- Materials science of abrasive pads

- Characterization of diamonds used in grinding
- Effects of variability in commercially available diamonds
- Stresses and deformations in domes and ogives
- Deformation of sapphire domes
- Optimization to avoid thermal shock in large heated/cooled glass plate
- Rheology of suspensions used in magnetorheological finishing
- CFD of flow of MRF fluids in constricted geometries
- Effects of coolants on borosilicate glass fracture and hardness
- Laser damage in MLD coatings
- Thermomechanical deformations in trigonal optical crystals
- Large deformations in thin, curved quartz plates
- First principles prediction of glass strength from glass chemistry
- Leakage failure in optical amplifiers
- Vibration optimization in fusion targets
- Chemomechanical deterioration of O-rings for amplifier assemblies
- Scratch resistance in optical crystals
- Subsurface damage in optical crystals vs optical glasses

6.0 STUDENT TELESCOPE PROJECT

Over the last two years, a student design team has been working on a telescope design project. The multi-disciplinary design team was composed of an optics major, a physics major and a mechanical engineering major. The telescope has a lightweight 16" primary mirror with a metering structure composed of composite tubes as shown in the CAD rendering in Figure 1. Final figuring of the optics will be completed soon, followed by assembly and testing. It is hoped that this project could spark interest in an intercollegiate design contest on telescopes; similar to the mechanical engineering contests for Mini-Baja all terrain vehicles.

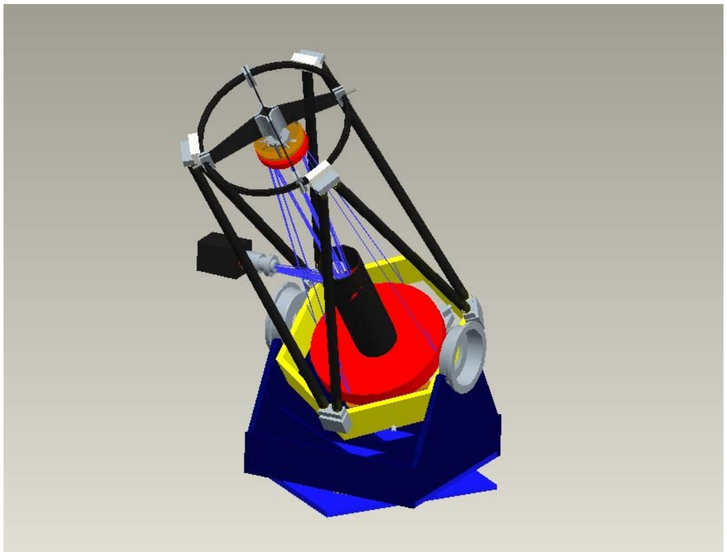

Figure 1: Student telescope project

7.0 SUMMARY

Students have the opportunity to specialize in optomechanics at the University of Rochester. Currently the students create their own program through the flexibility of the MS degree. In the future, there may be a formal specialization in optomechanics within both the optics and mechanical engineering MS program. Undergraduates also have the opportunity to take electives and to conduct research in optomechanics.

REFERENCES

[1] SigFit Reference Manual, Sigmadyne, Inc., Rochester, NY, 2011. (2011)
[2] Doyle, K.., Genberg, V., Michels, G., Integrated Optomechanical Analysis, SPIE, TT58, (2002)