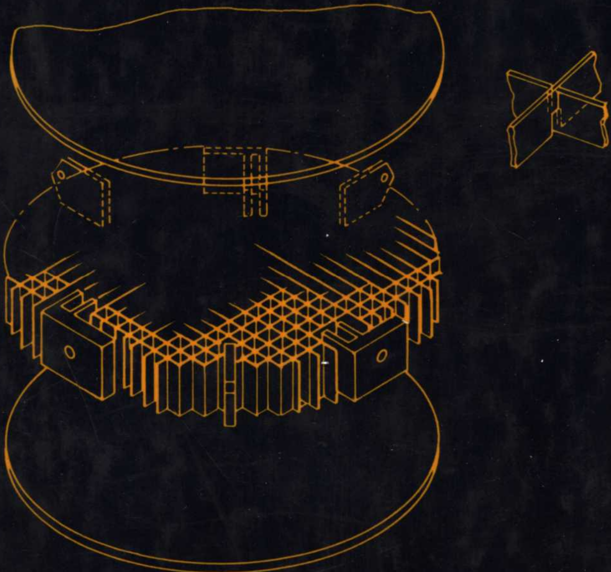
Optical Engineering / Volume 9

OPTO-MECHANICAL SYSTEMS DESIGN



PAUL R. YODER, JR.

Opto-Mechanical Systems Design

Paul R. Yoder, Jr.
Optical Group
Perkin-Elmer Corporation
Danbury, Connecticut

MARCEL DEKKER, INC. New York and Basel

Library of Congress Cataloging-in-Publication Data

Yoder, Paul R.
Opto-mechanical systems design.

(Optical engineering ; 9)
Includes bibliographies and index.
1. Optical instruments--Design and construction.
2. Mechanics, Applied. I. Title. II. Series: Optical engineering (Marcel Dekker, Inc.) ; v. 9.
TS513.Y63 1986 681'.4 86-4435
ISBN 0-8247-7347-0

MARCEL DEKKER, INC.
270 Madison Avenue, New York, New York 10016

Current printing (last digit):
10 9 8 7 6 5 4 3 2 1

PRINTED IN THE UNITED STATES OF AMERICA

About the Series

Optical science, engineering, and technology have grown rapidly in the last decade so that today optical engineering has emerged as an important discipline in its own right. This series is devoted to discussing topics in optical engineering at a level that will be useful to those working in the field or attempting to design systems that are based on optical techniques or that have significant optical subsystems. The philosophy is not to provide detailed monographs on narrow subject areas but to deal with the material at a level that makes it immediately useful to the practicing scientist and engineer. These are not research monographs, although we expect that workers in optical research will find them extremely valuable.

Volumes in this series cover those topics that have been a part of the rapid expansion of optical engineering. The developments that have led to this expansion include the laser and its many commercial and industrial applications, the new optical materials, gradient index optics, electro- and acousto-optics, fiber optics and communications, optical computing and pattern recognition, optical data reading, recording and storage, biomedical instrumentation, industrial robotics, integrated optics, infrared and ultraviolet systems, etc. Since the optical industry is currently one of the major growth industries this list will surely become even more extensive.

Brian J. Thompson
University of Rochester
Rochester, New York

Preface

In the preface to his book on *Fundamentals of Optical Engineering* (McGraw-Hill, 1943), Donald H. Jacobs wrote of his conviction that "in the design of any optical instrument, optical and mechanical considerations are not separate entities to be dealt with by different individuals but are merely two phases of a single problem." I have seen the truth of this statement many times during the design, development, and production of a variety of optical instruments—many of these being highly sophisticated systems intended for military and/or aerospace applications. The close interrelationship of the optical and mechanical disciplines cannot be ignored or left to chance encounters when the performance and reliability of the end item are vital to an important mission, such as photographing the farthest reaches of space with a spaceborne optical observatory. At the other extreme, the designers of even the simplest of optical instruments can benefit from a coordinated approach to the design problem.

This book is intended to be a compilation of opto-mechanical systems design guidelines and experiences. It tells how certain design tasks, such as the mounting of critical optical components in high-performance instruments, have been accomplished. The logic underlying those designs is outlined and, wherever possible, the success of the configuration used is evaluated. Included are considerations of analytical methods for predicting how a particular system or subsystem will react if exposed to specified environmental conditions. The mathematics of complete systems optimization is not stressed simply because the subject matter addressed here is so broad. A thorough analytical treatment of but a few of the design problems considered would fill a volume this size. Instead, this work concentrates on qualitative descriptions and references the optimization techniques explained elsewhere.

While many books on lens design and several on the design of mechanical structures and mechanisms have appeared in print since Jacobs first tried to tie these topics together, no author has given more than a fleeting consideration to them as an integrated topic. Indeed, Rudolph Kingslake specifically excluded considerations of the mechanical aspects of instrument design from the first five volumes of *Applied Optics and Optical Engineering* (Academic Press, 1965-1969), which he edited. It was not until 1980 when Robert E. Hopkins wrote on "Lens Mounting and Centering" in Volume VIII that an opto-mechanical topic was presented in any depth in that series.

The importance of the topic has been recognized, however, since many technical papers on opto-mechanical subjects have appeared in the *Journal of the Optical Society of America, Applied Optics, Journal of Scientific Instruments, Optical Engineering,* the *Soviet Journal of Optical Technology,* and similar publications. The subject has also been addressed by several professional society symposia, including OSA seminars, OSA workshops on optical fabrication and testing, and SPIE seminars on such topics as "Optics in Adverse Environments," "Opto-Mechanical Design," "Optical Specifications," and "Optical Systems Engineering." In assembling material for this book, I have unhesitatingly drawn upon many available sources to provide pertinent information. The above-listed journals and symposia proceedings are heavily referenced. Lens design per se is intentionally not stressed here.

One of the most significant problems in developing a reference book such as this was the determination of *how* to organize the material to be covered. I chose to supply information that should be useful to individuals involved in developing optical instrument designs and carrying those designs to completion of operational hardware. Usually such assignments include an optical design phase in which a collection of related optical elements is defined and a mechanical design phase, which incorporates the optics into a suitable mechanical surround. The goal of the total effort is to create an instrument capable of doing a specific job within specific constraints of size, weight, cost, physical packaging, and environment.

The discussion begins with a summary of the total opto-mechanical systems design process from conceptualization to end item evaluation and documentation. This introduces us to the major steps that must be taken to achieve a successful design. Next, we examine environmental influences and the traditional, as well as some newer, materials from which we can fabricate the optics and the mechanical parts of the instrument. Techniques for mounting various typical optical elements and groupings thereof, ranging in aperture size from a few centimeters to several meters in aperture, are considered next. Included are design and mounting considerations for individual lenses, mirrors, and prisms; refracting and catadioptric subassemblies; lightweight mirror substrates; mountings for mirrors with axis horizontal, vertical, or in variable orientation;

and design, fabrication, and mounting of metallic mirrors. We close with considerations of the structural design of optical instruments.

Familiarity on the part of the reader with geometric optics, the functions of optical systems, and the fundamentals of mechanical engineering is assumed. Theory and analytical aspects of opto-mechanical engineering are minimized in favor of descriptions of past and current design approaches.

It is expected that this work will be of interest to a wide range of readers including optical instrument designers, developers, and users; optical and mechanical systems engineers; structural and materials engineers; and students of the optical sciences. It is hoped that the material presented here will serve as a useful guide in the conception, design, development, evaluation, and use of optical instrumentation in military, space, and commercial applications.

Many people have helped in the preparation of this book by providing information, photographs, comments and suggestions, and permissions to use previously published material. Hopefully, credits have been given properly in all cases; I express here my thanks to these individuals and to any whose contributions have inadvertently been omitted. Of great importance was the assistance of the following associates at Perkin-Elmer: Richard German and Ross Gelb, who prepared many of the illustrations, and Jessica Monda, Helen Ryan, Jo Anne Gresham, and Stephanie Shearer, who typed much of the manuscript. I am especially indebted to Richard Babish, Peter Mumola, and Julianne Grace of Perkin-Elmer, Brian Thompson of the University of Rochester, the staff of Marcel Dekker, Inc., and my wife, Elizabeth, for providing the encouragement that kept this project moving to completion.

Paul R. Yoder, Jr.

Contents

1

The Opto-Mechanical Design Process

1.1. INTRODUCTION

Opto-mechanical design is a multistep, tightly integrated process involving many technical disciplines. It begins with the definition of one or more concepts for an item of optical hardware and a quantitative specification citing goals and/or firm requirements for that item's configuration, performance in a given application environment, etc. The design effort concludes only when that item is awarded a pedigree establishing its ability to meet the specification.

In this chapter, we address the design process as a logical sequence of major steps. Each of these steps is treated in a separate section. Admittedly our approach is idealized since few designs develop smoothly as planned. We endeavor to show how the process *should* occur and trust that those executing, reviewing, and approving the design will have the ingenuity and resourcefulness to cope with the inevitable problems and to bring errant design activities back into harmony.

Driving forces behind the methodology applied in the design process include schedule constraints, availability of personnel and other resources, perceived demands from the marketplace, and inherent costs of accomplishing and proving the success of the design. These we consider to lie within the province of project management, a subject clearly beyond the scope of this book.

A great influence on the opto-mechanical design process is the degree of maturity of the technology to be applied. For example, only a few years ago the design of the 2.4-m (96-in.) aperture Hubble Space Telescope capable of being lifted into earth orbit by the Space Shuttle would have been virtually impossible for a variety of reasons. One mechanical reason was the nonavailability of structural materials with the required blend of high stiffness, low density, and ultra-low thermal expansion characteristics. To have used aluminum, magnesium, or titanium in the telescope structure in lieu of the less familiar but promising new types of graphite epoxy composites actually employed would have severely limited the performance of the telescope in the varying operational thermal environment. The achievement of a successful state-of-the-art instrument design utilizing such new materials requires more theoretical synthesis and analysis, experimentation, and qualification testing than would a design involving only the application of tried and proven technologies.

Complex opto-mechanical systems such as the Space Telescope consist of many subsystems, each to be treated as a unique design problem with its own specifications and constraints. Subsystems generally consist of several major assemblies which, in turn, consist of subassemblies, components, and elements. By breaking the overall design problem down into a series of related but independently definable parts, even the most complex system will yield to the design process.

No one design can be cited in this chapter to illustrate all the various steps of the opto-mechanical design process. We therefore utilize a variety of unrelated examples involving military and aerospace instruments for this purpose. In real life, the magnitude of the effort required in any given step would be tailored to that appropriate to the specific design problem. The general approach to each step and to the overall design process would, however, be expected to follow the guidelines established here.

1.2. CONCEPTUALIZATION

The first step in the evolution of the design of an opto-mechanical system is recognition of the need for a device to accomplish a specific purpose. Usually the mere definition of a need brings to the minds of inventive engineers one or more vague concepts of the instrumentation that might meet that need. Knowledge of how similar needs were met by prior designs plays an important role at this point. Experience indicates not only how the device might be configured, but also how it should *not* be configured.

Functional block diagrams relating major portions of the system are valuable communication tools. Figure 1.1 shows one such diagram for a high-performance, long-focal-length camera system. This consists of two major assemblies: a lens cone/camera assembly and a stabilized mount assembly. It is applied in downward-looking aerial reconnaissance from high altitude. A variety of sensors and electromechanical control mechanisms are included in the lens cone/camera assembly to provide the required operational functions. At this stage in the design conceptualization, the detailed configurations of the individual "black boxes" in this system need not be known.

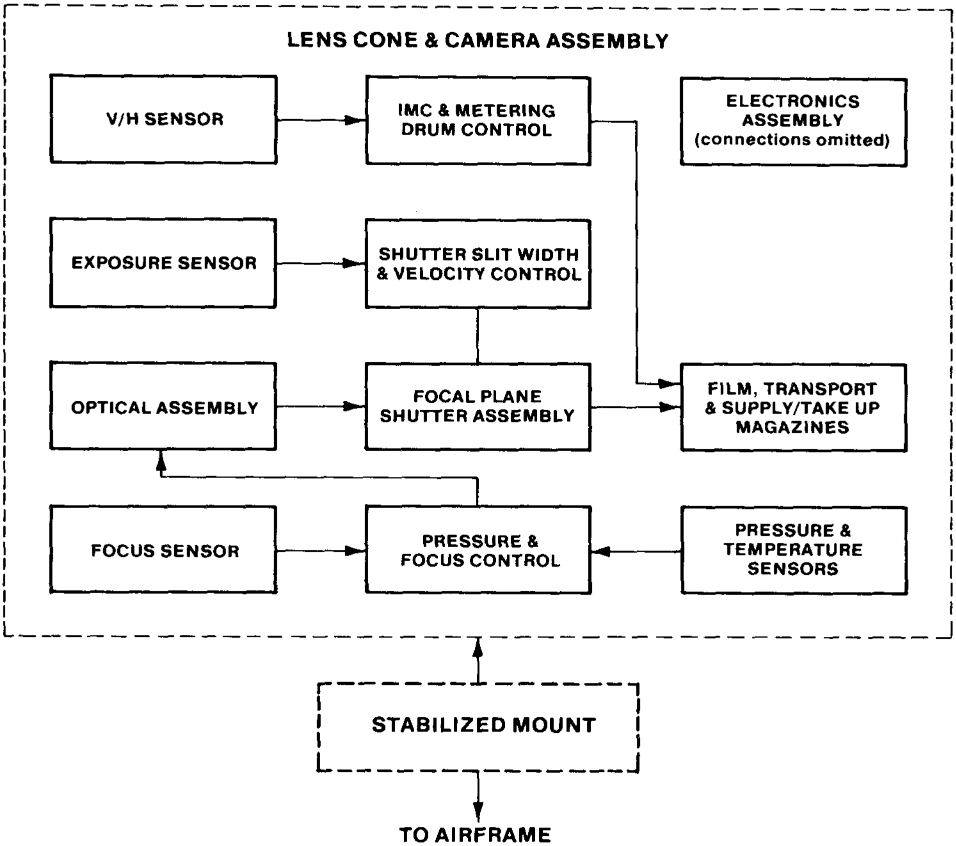


Fig. 1.1 Functional block diagram for a high-performance aerial reconnaissance camera system.

The opto-mechanical makeup of one concept for the "optical assembly" block in Fig. 1.1 is defined in Fig. 1.2. Here we see a lower-level block diagram indicating that the optical system consists conceptually of three separated lens groups, two fold mirrors, and a window. The lens groups and fold mirrors are mounted into cells or mounts that attach to a support structure. The window is mounted in a cover that enshrouds the optical system and also attaches to the support structure. This structure interfaces in turn to the camera assembly and to the airframe through the stabilized mount.

If a catadioptric Cassegrain-type optical system concept were to be advanced for this same application, one might expect an opto-mechanical block diagram of the form shown in Fig. 1.3 to apply. Here it is assumed that two

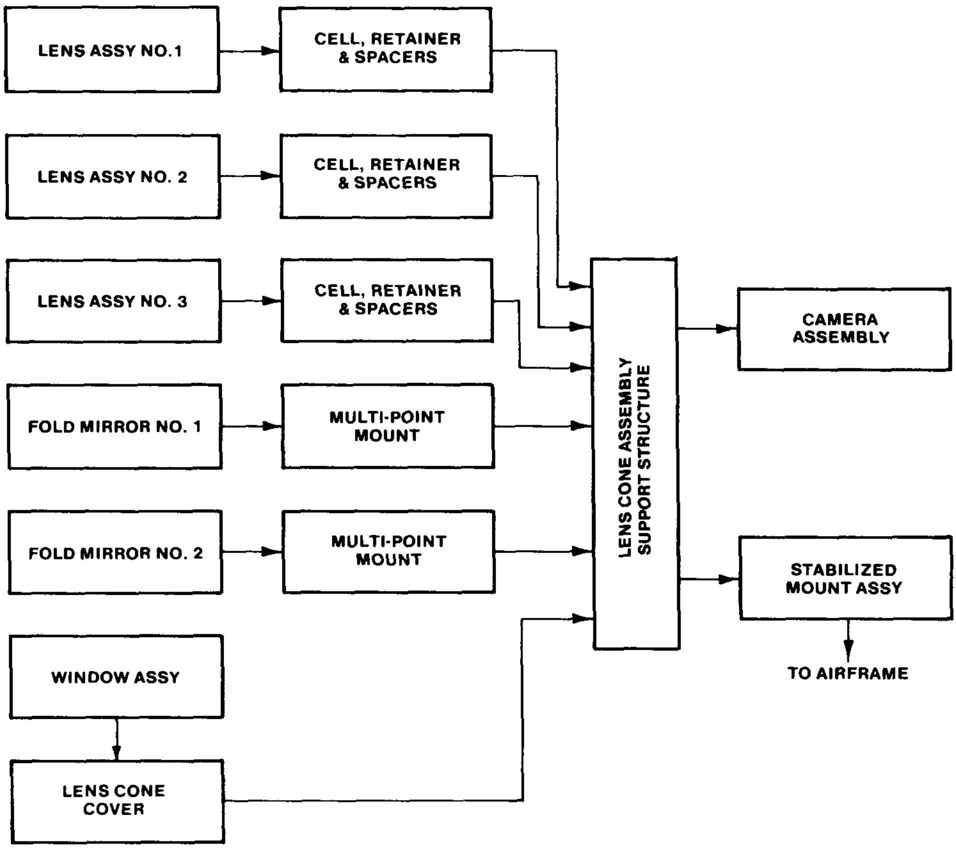


Fig. 1.2 Lower level block diagram of the "optical assembly" block of Fig. 1.1 configured as a folded, multilens system.

corrector plates and a field lens group are required for image quality and that the secondary mirror is to be supported from the innermost corrector plate. No folding mirrors are included in this concept.

As the function of the device to be designed is examined in more detail and the technical specifications begin to take form, the relative advantages and disadvantages of the suggested concepts can be established and weighed. Parametric trade-off analyses are often performed at this time in order to develop the interrelations between design variables. This helps disclose incompatibilities between specific requirements such as optical system specification combinations

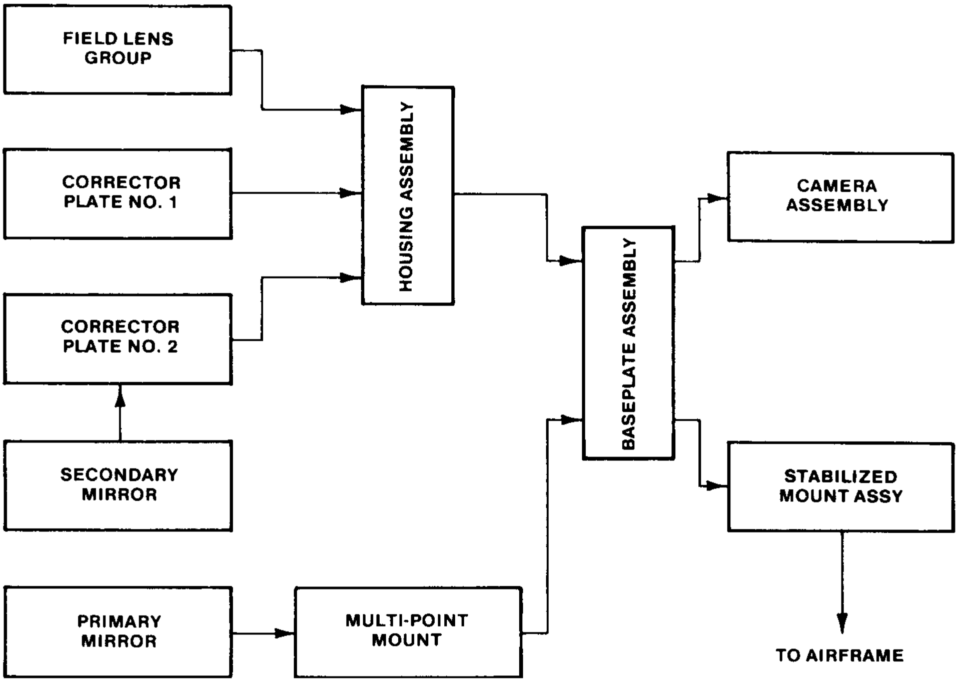


Fig. 1.3 Lower level block diagram of the "optical assembly" block of Fig. 1.1 configured as a catadioptric Cassegrain-type system.

that violate the Lagrange invariant (see Kingslake, 1983) in moving from object space to image space.

Rough estimates of the physical size and weight of the instrument if built along alternative lines also may prove helpful in identifying inconsistencies and in pointing out the more favorable of alternative concepts. Preliminary material choices made at this time need be no more specific than to assume that glass would be used in lenses and windows, that reflective components would be glass or metal, that optical component thicknesses would be 10 percent of their diameters, and that the number of optical components required in the optical system would lie between two reasonable extremes. From the mechanical viewpoint, it would be appropriate to make a tentative choice between alternative structural concepts such as a lightweight truss covered by a thin protective skin (appropriate to a spaceborne scientific payload), a cast aluminum housing (appropriate to a photographic lens assembly), or a tubular steel housing (appropriate to a submarine periscope). Conceptual layouts of the most viable concept(s) then can be prepared for evaluation and to serve as the starting points for detailed preliminary design.

1.3. PERFORMANCE SPECIFICATIONS AND DESIGN CONSTRAINTS

Two of the most important inputs to the design process are the performance specification and the definition of imposed constraints. The former sets forth the prospective user's definition of how an acceptable end item will work, while the latter defines the physical limitations, such as size, weight, configuration, environment, and power consumption, that affect interfaces with the rest of the world. In the case of a scientific payload for an interplanetary space probe, these generally would take the form of several separate, complex, and lengthy documents. In the simplest cases, the "specification" would consist of one short document giving a few general requirements; most parameters would be left to the discretion of the optical and mechanical designers and engineers.

A reasonably complete list of items that should be considered in the typical performance specification and/or constraint definition for an optomechanical system may be found in Table 1.1. These items are not necessarily in

Table 1.1 Checklist of General Design Features Typically Included in Specifications and Constraint Definitions

Performance requirements
Size, shape, and weight limitations
Interfaces (optical, mechanical, electrical, etc.)
Operating environment (temperature, pressure, vibration, shock, humidity, acoustic noise, contamination, etc.)
Force loads (static and dynamic)
Duty cycle and useful life requirements
Maintenance and servicing provisions (access, fits, clearances, torquing, etc.)
Emergency or overload conditions
Center of gravity and lifting provisions
Human-instrument interface requirements and restrictions (including safety aspects)
Electrical requirements and restrictions
Materials selection and limitations
Finish/color requirements
Corrosion, fungus, rain erosion protection requirements
Inspection and test provisions
Electromagnetic interference restrictions
Special markings or identifications
Storage, packaging, and shipping requirements