1

INTRODUCTION

Despite our best efforts and intentions, Mr. Murphy—a rather jovial fellow who happens to be a bit sensitive to these things, but who also has a fondness for *Schadenfreude*—will remind anyone developing optical hardware of his inescapable Law, whether they like it or not. For those who are not prepared, the reminder will be unexpected, and schedules, budgets, and careers will eventually be broken; for those who are prepared, his reminder will be much less painful—and soon forgotten, as the customer's happiness at receiving working hardware reminds us why we are engineers in the first place.

Fortunately, Pasteur's antidote to Murphy's near-deadly "snakebites"—that chance favors the prepared mind—is our opportunity to remove most of the fatalism from engineering. The type of preparation that this book provides goes under the name of *optomechanical engineering*—an area of optical systems engineering where "the rubber meets the road," and thus has the highest visibility to managers and customers alike [1].

It is sometimes said that optomechanical design is a relatively new field, but the truth is a bit more complicated. Not surprisingly, it is as old as optical engineering itself, a field that dates back to at least the early 1600s when the Dutch were assembling telescopes.[1] Notable contributions by people who

---

[1] The early 1600 date given in this chapter is that when theory was first turned to engineering practice in the form of complex optical instruments such as telescopes.

Optomechanical Systems Engineering, First Edition. Keith J. Kasunic.

are otherwise known as great scientists—but should also be recognized as optomechanical engineers—include:

- Galileo—While he did not invent the telescope, a practical telescope architecture using refractive (lens) components is named after him.
- Isaac Newton—To develop his theories on the nature of light, he invented the first practical telescope using reflective (mirror) components.
- James Clerk Maxwell—In addition to his brilliant discovery of the electromagnetic nature of light, he developed a structural theory of trusses and experimented with photoelasticity and kinematic mounts.
- Joseph Fourier—He made many contributions in the areas of heat transfer and thermal design, including the discovery of Fourier's law of conduction and the Fourier transform for analyzing vibrations, heat-transfer problems, and more recently, electrical circuits.
- William Thomson (aka Lord Kelvin)—He is best known for his work in thermodynamics, developing the Kelvin temperature scale. In addition, he deserves to be recognized for his work in kinematics, inventing the Kelvin kinematic mount.

In short, these were people who were trying to solve difficult physics problems but were unable to do so until they first solved the instrumentation problems of how to make an apparatus stiff, stable, repeatable, and so on, that is, solve the state-of-the-art optomechanical problems.

More recently, we are still trying to solve difficult problems including the following applications and even quantum optomechanics [2]:

- Aerospace: infrared cameras, spectrometers, high-power laser systems, etc.
- Biomedical: fluorescence microscopy, flow cytometry, DNA sequencing, etc.
- Manufacturing: machine vision, laser cutting and drilling, etc.

In the following sections of this chapter, we first take a look at what a typical optomechanical system might consist of (Section 1.1), the skills needed to engineer such a system (Section 1.2), and the mindset needed to do this efficiently (Section 1.3).

1.1 OPTOMECHANICAL SYSTEMS

If we buy an optomechanical system today, what would we expect to get for our money? Figure 1.1 illustrates a complex biomedical product known as a swept-field confocal microscope—a microscope with some unique features that allow it to image over a wide field-of-view with high resolution [3, 4].

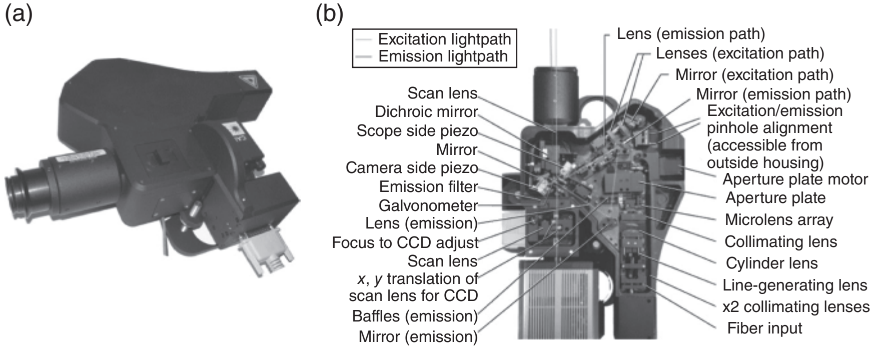

FIGURE 1.1 A complex optical system such as a swept-field confocal microscope requires a large number of optomechanical components packaged into a small volume. Credit: LOCI and Laser Focus World, Vol. 46, No. 3 (Mar. 2010) [3].

Given its complexity, the designers of this microscope had to struggle with many issues that are not obvious to the eye, including:

- Assembly and alignment—Can the optical components all be assembled in a small package and maintain critical alignments such as the “Focus to CCD” distance (for which an adjustment is provided)?
- Structural design—Are the overall structure and the optical submounts stiff enough to keep things in alignment due to self-weight or shock loading?
- Vibration design—Have scan mirror vibrations been isolated from the optics and prevented from causing the optics to move ever so slightly (but more than is acceptable)?
- Thermal design—With components such as the piezos and galvanometers dissipating heat in such a small volume, is there even enough surface area to transfer this heat without the external box temperature getting excessively hot?
- Kinematic design—If the microscope needs to be repaired, is there a way to remove critical optics that allows them to be replaced in the field, without a major realignment at the factory?
- System design—Have all the interactions between the elements been considered, for example, the effects of heat on the optics?

Before getting to these topics, it is important to first understand that common to all optomechanical systems is the use of electromagnetic waves known as “light” (Fig. 1.2). This refers to the wavelength of these waves—on the order of 1 μm, but extending down to 0.1 μm or so and up to ~30 μm—and distinct from “radio” waves, with much longer wavelengths. Controlling the curvature and direction of optical wavefronts with lenses and mirrors is what

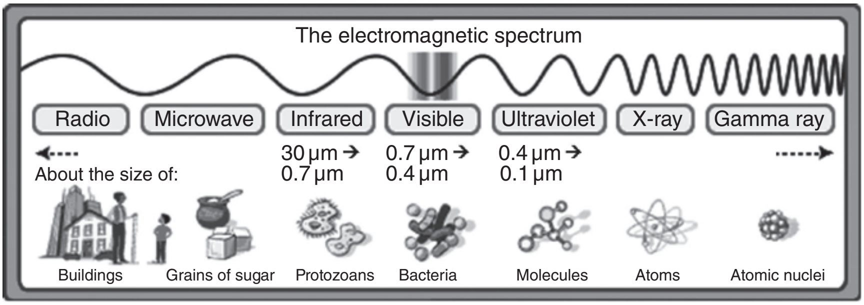

FIGURE 1.2 Optical electromagnetic wavelengths ("light") can be divided into infrared, visible, and ultraviolet bands. Credit: NASA (www.nasa.gov).

allows us to create optical images, or determine the wavelengths present, or measure the power transported by a wavefront. Keeping mechanical parts aligned and stable to <1 μm—an extremely small dimension equal to ~40 micro-inches (or 0.04 milli-inches, often pronounced in abbreviated form as "mils")—is one of the many challenges of optomechanical engineering.

1.2 OPTOMECHANICAL ENGINEERING

So an optomechanical system has a few lenses and a detector—how difficult can this be to design? As we have just mentioned, the small size of an optical wavelength—and thus the mechanical accuracy required—is one of the difficulties. Paul Yoder and Dan Vukobratovich have published the majority of recent books showing us many of the implementation difficulties, and have many useful details and hints on building hardware [5–10]. Even "just" a packaging job is not straightforward, for example, as many laser jocks have discovered when trying to convert their laboratory hardware into a commercial product (Fig. 1.3).

An example of one of the steps required for the transition from lab to marketplace—or even optical designer's desk to working prototype—is shown in Figure 1.4. Here, a lens designer has determined that a three-lens system is required to meet the customer's needs (or "requirements"). The lens designer's deliverable to the optomechanical engineer is an optical prescription from lens design software such as Zemax or Code V, consisting of lens geometries (surface radii and diameter), materials, and spacings between the lenses.

The lens designer must also provide a tolerance analysis showing how sensitive each lens is to misalignments such as tilt, centration, and spacing errors—and how much of each is allowed. In addition, the lens designer must deliver a fabrication analysis for each lens, specifying the tolerances on the lens surfaces, refractive indices of the lenses, and so on—a topic we will look

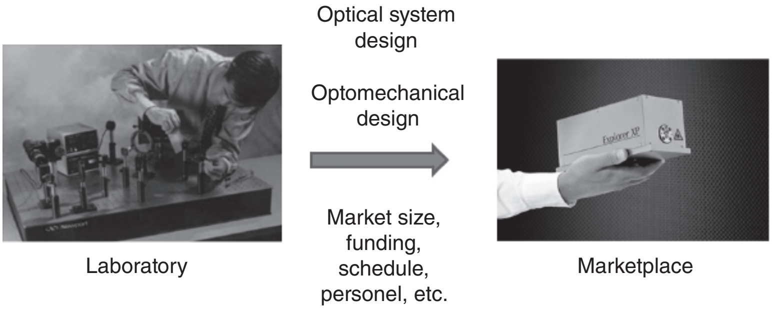

FIGURE 1.3 The transition from laboratory to marketplace is critically dependent on the skills of the optomechanical engineers. Photo credits: Permission to use granted by Newport Corporation; all rights reserved.

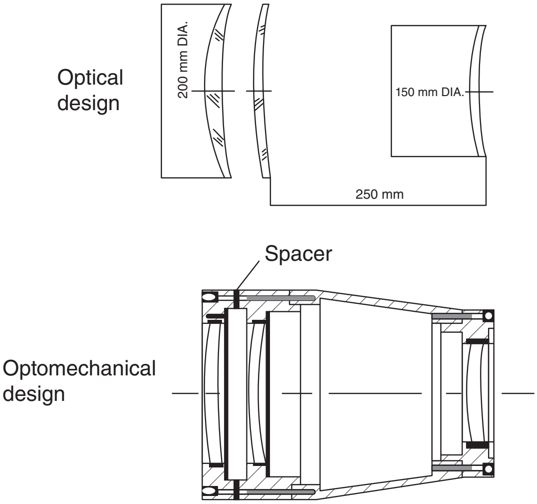

FIGURE 1.4 An example illustrating the steps required to move from an optical design prescription to a complete optomechanical design. Credit: G. E. Jones, "High Performance Lens Mounting," Proc. SPIE, Vol. 73, pp. 9–17 (1975).

at in detail in Chapter 3. Ideally, the optical prescription, alignment analysis, and fabrication analysis must be developed in coordination with the optomechanical engineer; in practice, this is not always done, with the consequences illustrated with an example in Section 1.3.

Given these inputs from the lens designer, what the optomechanical engineer must then determine is as follows: are the fabrication and alignment tolerances (i.e., allowable variations) feasible, given the manufacturing, technical, environmental, cost, and schedule constraints? That is, is it possible to take the lens designer's prescription and convert it into manufacturable hardware such as that shown in the bottom graphic of Figure 1.4?

This is never a trivial task, and it is possible to undo the lens designer's work with poor optomechanical engineering. What makes the task nontrivial are the requirements that make optomechanical engineering so challenging: (i) the extremely small ("tight") fabrication tolerances, (ii) the extremely tight assembly (alignment) tolerances, perhaps <1 μm for displacements and 1 μrad for angular misalignments, and (iii) the extreme sensitivity to environmental conditions such as temperature, shock, and vibration.

Given these requirements, the design questions that must be answered for the lens assembly shown in Figure 1.4 include the following:

- Can we make (or buy) the optics to the quality specified by the lens designer?
- How can we mount the lenses without warping them?
- What happens when the lenses change temperature?
- What happens when the lenses are on a vibrating platform such as a car, boat, or satellite?

These questions also illustrate the topics that will be covered in this book: (i) fabrication errors (see Chapter 3), (ii) misalignments between lenses (Chapter 4), (iii) strain-induced alignment errors (Chapters 5, 6, and 7), (iv) temperature-induced alignment errors and changes in refractive index (Chapter 8), and (v) kinematic mounting principles (Chapter 9). Optomechanical engineering thus starts with the fabrication of the lenses, mirrors, and so forth that make up the system. These building blocks are collectively known as "elements" or "components" and an inability to manufacture them with the required quality results in a system that will not meet specs. For example, a diffraction-limited, *f*/1 mirror of 2 m diameter is not straightforward to build, and fabrication technology may be the limiting factor in its optical performance. Yet if the mirror needs only to collect photons and need not generate good image quality, then a large-diameter optic becomes more feasible. The ability to meet specs thus depends in part on how well the image quality requirements of the system match up with the optical quality available from the fabrication process.

After fabrication, optical elements are assembled into an instrument or system; this requires that they be accurately aligned with respect to each other to insure crisp, high-resolution image quality. The distance between the primary and secondary mirrors in the Hubble Space Telescope, for example, was ~5 m—to a tolerance of ±1.5 μ, or 1 part in 1.7 million! Typical alignment problems for an optical system include: (i) the tilt angle with respect to either of the two axes perpendicular to the optical axis; (ii) decenter, or displacements along either of those two axes; (iii) despace, or the incorrect placement of one element with respect to another as measured along the optical axis; and (iv) defocus, a specific type of despace pertaining to the placement of the detector with respect to the imaging optics as measured along the optical axis. These assembly alignments and their effects on optical performance are reviewed in Chapter 4.

The most critical factors determining whether or not an optical system can be built are the fabrication and assembly tolerances; these are the acceptable variations of the fabrication and assembly parameters. Tolerances are determined by how sensitive performance is to small changes in system-level parameters such as f/#. This sensitivity flows down to component-level tolerances through the dependence of f/# (for instance) on aperture and effective focal length (EFL); EFL, in turn, depends on the refractive indices, surface curvatures, and thickness and spacings of the lenses in the system. An EFL that is extremely sensitive to changes in index, for example, is considered difficult to fabricate; similarly, a lens-to-lens spacing that is highly sensitive to misalignments is difficult to assemble.

Moreover, tight assembly tolerances imply that the optics are also extremely sensitive to vibration and changes in temperature. Once aligned, an optical system will usually remain so on a vibration-isolation table in a climate-controlled building; however, the system may become useless once it is moved out into the field, where environmental effects—including temperature changes, shock, vibration, humidity, ocean spray, vacuum, and radiation—become important. The two most common problems are temperature and vibration, either of which can quickly destroy the instrument's ability to meet a high-resolution image-quality spec. Even systems that are precisely fabricated and accurately aligned can fail to meet image-quality requirements when, for example, the temperature drops below freezing or the instrument has been bouncing around in the back of a truck during a bumpy off-road trek through the Colorado mountains.

In short, *better design performance does not necessarily translate into a better optical system.* Many other factors affect overall performance, including fabrication, alignment, and environmental influences such as temperature and vibration. The sensitivity to fabrication tolerances and misalignments is the key determinant of cost and producibility. The best design is therefore one that has large tolerances in all areas.

Optomechanical systems consist, of course, of more than lens assemblies; an example of a more complex system is shown in Figure 1.5. Here, the authors illustrate the use of hardware "building blocks" previously made for other projects to save development time and money on future projects—a much-needed approach for the aerospace business which the authors are in.

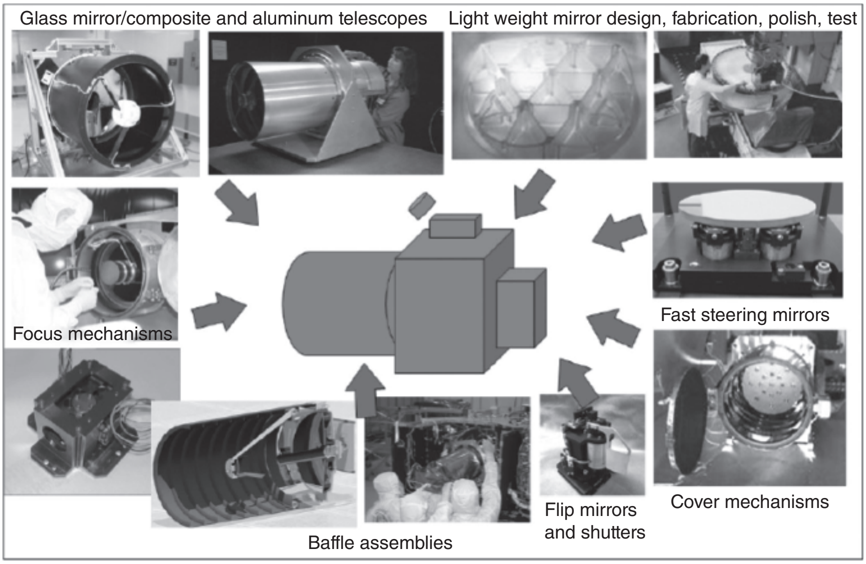

FIGURE 1.5 A complex optomechanical system requires the coordination of many different disciplines and technologies. Credit: Tony Hull and Mark Schwalm, "Spaceborne telescopes on a budget: paradigms for producing high-reliability telescopes, scanners, and EO assemblies using heritage building blocks," Proc. SPIE, Vol. 8044 (2011).

Shown in the figure are a number of optomechanical assemblies and subsystems such as a fast-steering mirror, focus mechanism, and a telescope sub-assembly (lightweight mirrors, metering structure, etc) which are all combined to produce a complex telescope assembly. The optical prescription in this case—that of the primary and secondary mirror—is simpler than that of the lens assembly shown in Figure 1.4; the optomechanical design, on the other hand, is clearly more intertwined with the optical design—the available scan angle for the fast-steering mirror must be consistent with the field-of-view of the optics, for example—illustrating the need for a systems-level approach to optomechanical engineering.

The systems approach to optomechanical engineering is also necessary for the lens assembly shown in Figure 1.4. For example, estimates of athermalization for such a lens often include only the mechanical effects of thermal expansion; also necessary, however, are the optical effects of change in refractive index with temperature. Only the combination of these two—an integrated optomechanical systems design—will produce a system that is relatively insensitive to temperature changes. Thus the appropriate mindset for developing optical hardware must *not* be one of the lens designer saying to the optomechanical engineer "Here's the lens design—go for it!"; instead, a collaborative approach involving all relevant engineering disciplines answering the question “What should the system look like, given the technical, manufacturing, cost, and schedule constraints?” must be used. Section 1.3 illustrates the concept in more detail.

1.3 OPTOMECHANICAL SYSTEMS ENGINEERING

It is often the case that an optomechanical designer will want to jump right into the “epoxies-and-fasteners” (aka “glues-and-screws”) details of optomechanical engineering, without first doing technical and cost trades of design options. These trades are required for an overall system approach to the problem, so that even without having the time or budget to do formal trades, it is invaluable to at least take a higher-level look at an initial design from the perspectives of manufacturability, assembly, optical alignment tolerances, and so on.

It takes a certain mindset to do this right, and it is difficult to find people with sufficient technical expertise to know the trades, but not so “detail oriented” at the beginning as to lose sight of the big picture. It is important to get the details right, but it is even more important to get the architecture going in an intelligent direction. As with aiming errors on a long pool table, engineering errors at the beginning of a project propagate to create huge delays in schedule and cost overruns in budget (Fig. 1.6) [11], resulting in missed “shots” that will not impress the customer. In these cases, even heroic amounts of “glues and screws” effort cannot pull a successful story out of the fog of failure.

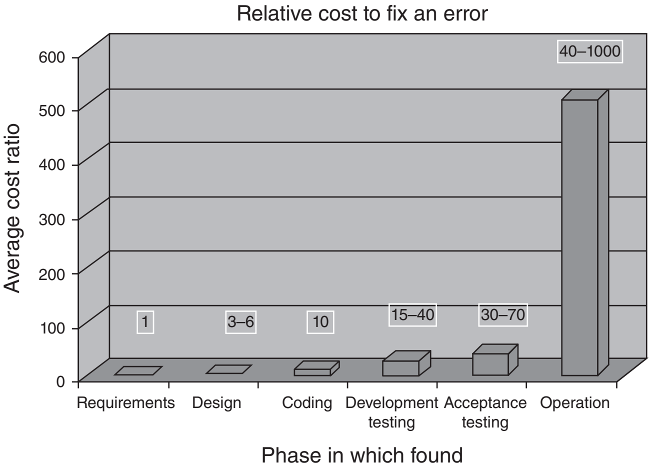

FIGURE 1.6 Engineering errors at the beginning of a program propagate to create huge budget (and schedule) overruns if not corrected early on. Source: NASA Johnson Space Center [11].

Recent highly-visible examples of "missed" optical engineering projects include the Hubble Space Telescope [12], a classified program reported on by *The New York Times* [13], and the James Webb Space Telescope (JWST) [14]. In the case of the Hubble, the lack of end-to-end testing of the telescope's images was the root cause of a $250 million error which required an on-orbit repair mission in space. The technical "glitch" that the end-to-end testing would have uncovered was an error in fabrication of the shape of the primary mirror—an error which itself was caused by a mistake in the assembly of the calibration optics used to measure the shape. This mistake was not so much one of architectural design as it was a Murphy's Law cascade of smaller errors which may or may not have been identified with better optomechanical engineering training and procedures.[2]

The classified program was covered in depth in *The New York Times* [13], where it was disclosed that a major spy satellite program was unable to deliver the performance promised by the aerospace contractor. After $5 billion was spent, the optical system was still not ready for launch. After more delays, what was eventually launched was an investigation into the root cause of the problem; an aerospace executive concluded: "There were a lot of bright young people involved in developing the concept, but they hadn't been involved in manufacturing sophisticated optical systems. It soon became clear the system could not be built." This seems to be a clear case of an architectural error, a fundamental mistake in a basic concept which was only later found to be flawed. Further underlining the architectural error was another statement from an investigator that "The train wreck was predetermined on Day 1." This is, of course, *very* strong language, but strong language is required after $5 billion has been wasted; the importance of an optomechanical systems engineering approach to avoiding such errors could not be clearer.

Finally, it was until recently generally agreed that the cost overruns on the JWST—approximately $9 billion is now needed to complete the project, compared with an estimated $2 billion at the beginning of the project—were based not on technical performance issues but on errors in initial budgeting [14]. As the JWST program has recently discovered, however, the distinction between technical performance and budget performance is not always clear cut, as the two are almost always entangled. For example, Figure 1.7a shows an imaging camera, with three lenses creating an image on a digital focal-plane array

---

[2] Specifically, the instrument used to measure the shape of the primary mirror (a null corrector) was not aligned properly because a non-optical surface was used by accident. This occurred because the paint which was used to blacken the non-optical surface was unintentionally peeled off—exposing reflective aluminum after adhesive tape that was used to keep dust off the optics was removed. In retrospect, we can see a number of possible ways to have prevented this sequence from becoming catastrophic, such as making end-to-end measurements of the system performance to check for such errors. See Ref. [12] for more details.

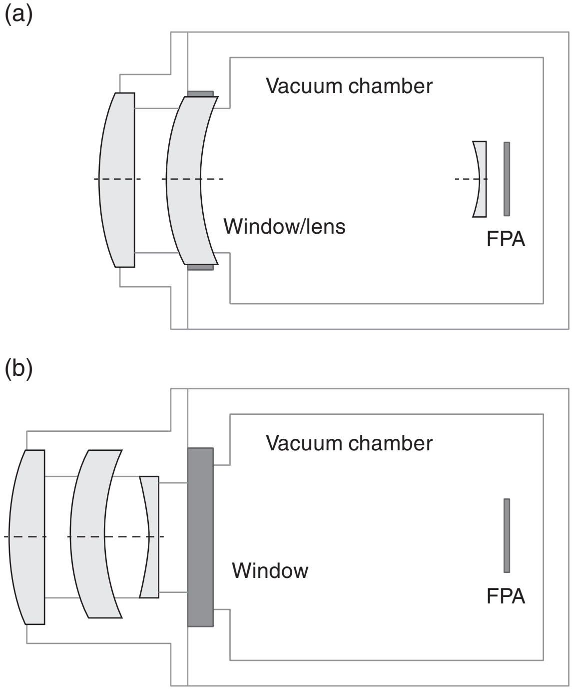

FIGURE 1.7 In (a), a lens design with an external lens, curved window, and field flattener is extremely difficult to align. In (b), all lenses are combined into a compact mount to ease alignment, assembly, and test.

(FPA). The FPA is in a vacuum chamber, as is the lens located near it (known as a field flattener; see Ref. [1] for more details). In addition, the lens designer—in an effort to reduce the parts count—has combined the function of a lens and the vacuum window by putting curvature in the window itself, thus reducing the number of parts by one lens. On this basis, a cost estimate was made for a potential customer—including the cost “savings” from combining optical elements—who agreed to fund the project.

While it seems reasonable to combine elements like this to reduce the parts count, what is found instead is that this design is not manufacturable, and the cost estimate was quickly exceeded. Specifically, the accumulation (or “stackup”) of tolerances on the many individual mechanical parts required an extensive assembly and alignment procedure. As we will see in Chapter 4, the lenses must all be aligned to a certain degree with respect to each other in terms of their spacings, tilt angles, and centering. This is next to impossible for the design shown in Figure 1.7a, given the large separations of the optics, the individual parts on which they are mounted, the mechanical paths connecting the parts, and the tight spacing and centration tolerances this design required.

Furthermore, even if the two adjustable lenses—the field flattener and the external lens—could be aligned with respect to each other and the fixed window, the structural and thermal stability of the adjustments must be sufficiently robust to maintain alignment as the camera is vibrated or its temperature changes.

In addition, testing of the optics shown in Figure 1.7a is extremely time-consuming, as the vacuum chamber is an integral part of the optical design, and the two sub-systems cannot be tested independently. Seeing these manufacturing difficulties is not so much a question of design "elegance" as it is a basic understanding of optomechanical engineering principles, which neither the lens designer nor the mechanical engineer on this project had. As a result, the project went ahead as planned and was quickly behind schedule and over budget—despite many internal reviews and "checked boxes" with project management, quality assurance, and so on.

An alternative architecture is shown in Figure 1.7b, where the field flattening lens has been removed from the vacuum chamber, and the window curvature has been removed and put into a separate lens element. This was not a difficult task but required some tweaking of system requirements and creative thinking on the part of the lens designer. The result is that there are now three lenses and a flat window, but the design does not require heroic efforts to assemble, align, and test. Instead, the three lenses can be aligned and tested as a unit in a compact mount and then bolted to the vacuum chamber for final positioning of the image on the FPA. In addition, the structural and thermal stability is much easier to maintain over the smaller package size, as we will see in Chapters 5, 6, 7, 8, and 9.

So based on the optomechanical system architecture shown in Figure 1.7a—which did not take basic manufacturing and alignment trades into account—the budget was proven to be grossly underestimated; the much lower-cost estimate for the design shown in Figure 1.7b, on the other hand, was not exceeded, and this version of the camera is in use today. So is the cost over-run for the Figure 1.7a design a problem of errors in initial budgeting—or instead one of poor engineering? In Figure 1.7a, the mechanical engineer did not have the required optomechanical skills to assess manufacturability; in other cases, the optomechanical engineers are not included in the discussion at the beginning and are left to salvage whatever they can from the optical design that is given to them after the project is funded. In both situations, the budget problem can be traced back to the lack of utilization of the technical skills required to get the job done.

The most important technical skill is that of system design, and from this perspective, "collaborative" is more than a buzzword to be used on employee annual review forms. Instead, it is how a *system* is designed—as distinct from a component, where an individual engineer has pretty much all the information they need to sit down and design parts to the point where they can be fabricated.

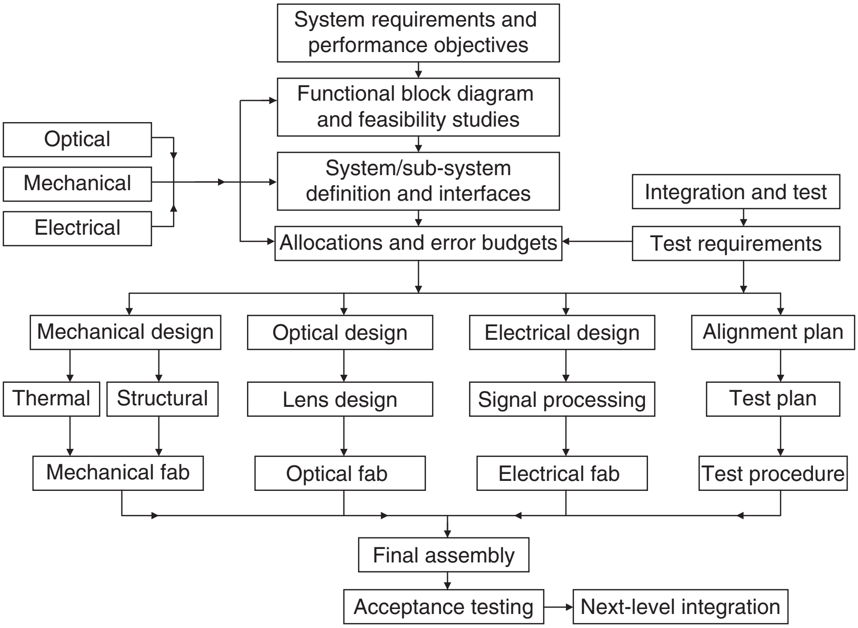

FIGURE 1.8 Optomechanical engineers must be involved at both the system architecture (top left) and detail design (middle left) phases of product development. Adapted from Keith J. Kasunic, *Optical Systems Engineering*, McGraw-Hill (2011).

A system, on the other hand, requires the knowledge and experience of many people with widely varying skills and backgrounds—optical engineers, mechanical engineers, electrical engineers, software engineers, manufacturing engineers, project engineers, systems engineers, and project managers (Fig. 1.8). It does not require large meetings with all these people on a daily basis, but it does require coordination—that is, collaboration—between the key interfaces such as the optical and optomechanical engineers (as we will see in detail in this book), or optical and electrical engineers (for an imaging system which uses digital FPAs, for example), or the many other interfaces that the systems engineer is responsible for [1].

Summarizing, a problem that has caused cost and schedule overruns on many projects is that the entire system design is disjoint from the beginning. That is, the optical engineers work to design a lens based on requirements given to them by the systems engineer, and then throw the lens design “over the wall,” that is, without inputs from the optomechanical engineer as to fabrication requirements, alignment tolerances, vibration instabilities, thermal drift, and so on.

System architecture is the most important thing to get right, and the optomechanical system is as important as the others [1]. Not including the optomechanical engineer at the beginning guarantees that, aside from leaving the optomechanical engineers feel left out of the process, they will not have the "big picture" needed to make intelligent choices. So through no fault of their own, the emphasis quickly turns to "glues and screws" details, which is often the best that can be done at a later stage of a design effort. The goal of this book, then, is to review the fundamental concepts and technical skills needed by optomechanical engineers—not the "glues and screws" details available in other books [5–9]; the intended audience is not only the mechanical design community, but also the many other types of engineers—optical, stress, thermal, electrical, systems, project, and so on—and managers who may be working to build optical hardware.

From the perspective of managing optomechanical engineering projects, there are "no right answers" to a design problem, meaning that there are a million wrong answers, and anywhere from only 1 to 10 answers—order of magnitude—that will work. So even if the system architecture is established collaboratively, the project will still fail if the engineers do not have the skills, experience, and judgment to find one of these right answers within a reasonable schedule and budget.

The most crucial of these skills for the optomechanical engineer is the ability to perform an initial system-level evaluation of manufacturing, alignment, and assembly before investing in detailed performance models or calculations. It is impossible to include everything in this assessment, so the purpose of the analysis and calculations is to do as much up-front work as is practical within the time and budget constraints. As with all trades, it is difficult to maintain a balance between these expenses, and it is usually best to build hardware as soon as possible.

Finally, it is easy to fall into the mistake of thinking that management processes for monitoring progress will insure an on-time, on-budget project that meets all of its technical goals. In the experience of former NASA Administrator Michael Griffin, however, systems engineering processes "… do not help to distinguish a good design from a poor one, nor can they make a poor design better" [15]. Management checklists are important, but technical skills are even more so. As Griffin summarizes in a panel discussion on his experiences: "In engineering, like flying, you need to follow the checklist, but you also need to know how to engineer" [16].

Along these lines, this book starts with an overview of optical engineering, to show how the requirements on the optical system determine what the optomechanical system must do. The overview includes optical fundamentals (Chapter 2) and the fabrication (Chapter 3) and alignment (Chapter 4) of optical components. From there, the fundamental principles of optomechanical engineering are applied to the design of optical systems, including the structural design of mechanical and optical components (Chapters 5 and 6), structural dynamics (Chapter 7), thermal design (Chapter 8), and kinematic design (Chapter 9). The book closes with a summary chapter tying everything together from a system—but not a process—perspective (Chapter 10).

REFERENCES

1. K. J. Kasunic, *Optical Systems Engineering*, New York: McGraw-Hill (2011).
2. M. Aspelmeyer, S. Gröblacher, K. Hammerer, and N. Kiesel, “Quantum optomechanics: throwing a glance,” J. Opt. Soc. Am. B, Vol. 27, No. 6, pp. A189–A187 (2010).
3. B. Vogt, L. Yan, M. Szulczewski, and K. Eliceiri, “Swept field confocal overcomes point-scanning microscopy limitations,” Laser Focus World, Vol. 46, No. 3, p. 55 (2010).
4. R. Liang (Ed.), *Biomedical Optical Imaging Technologies*, New York: Springer-Verlag (2013).
5. R. E. Fischer, B. Tadic-Galeb, and P. R. Yoder, Jr., *Optical System Design* (2nd Edition), New York: McGraw-Hill (www.mcgraw-hill.com) (2008), Chaps. 16–18.
6. P. R. Yoder, Jr., *Opto-Mechanical Systems Design* (3rd Edition), Boca Raton: CRC Press (www.crcpress.com) (2005).
7. P. R. Yoder, Jr., “Mounting optical components,” in M. Bass, E. W. Van Stryland, D. R. Williams, and W. L. Wolfe (Eds.), *Handbook of Optics* (2nd Edition), Vol. 1, New York: McGraw-Hill (www.mcgraw-hill.com) (1995), Chap. 37.
8. P. R. Yoder, Jr., *Mounting Optics in Optical Instruments* (2nd Edition), Bellingham: SPIE Press (www.spie.org) (2008).
9. D. Vukobratovich, *Introduction to Optomechanical Design*, SPIE Short Course Notes (www.spie.org) (2009).
10. D. Vukobratovich, “Optomechanical systems design,” in J. S. Acetta and D. L. Shoemaker (Eds.), *The Infrared and Electro-Optical Systems Handbook*, Vol. 4, Bellingham: SPIE Press (www.spie.org), Chap. 3.
11. “Error Cost Escalation through the Project Life Cycle,” NASA Johnson Space Center (2004), ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100036670.pdf. Accessed January 13, 2015.
12. J. Hecht, “Saving hubble,” *Optics and Photonics News*, March 2013, pp. 42–49.
13. P. Taubman, “Death of a spy satellite program,” *The New York Times*, November 11, 2007, p. 1.
14. A. Svitak, “Technical, cost issues persist for Webb telescope,” *Aviation Week & Space Technology*, July 22, 2013, http://aviationweek.com/awin/technical-cost-issues-persist-webb-telescope. Accessed January 13, 2015.
15. M. D. Griffin, “How do we fix system engineering?,” 61st International Astronautical Congress, Paper IAC-10.D1.5.4; September 27–October 1, 2010; Prague, Czech Republic (2010).
16. N. J. Slegers, R. T. Kadish, G. E. Payton, J. Thomas, M. D. Griffin, and D. Dumbacher, “Learning from failure in systems engineering: a panel discussion.” Wiley Online Library (2010). doi:10.1002/sys.20195.