2

Integrated Models

In the following, we shall in more detail introduce the rationale for and concepts of integrated modeling. Integrated modeling is closely related to systems engineering and to the task of setting up and verifying fulfillment of performance specifications. We therefore first comment on systems engineering for large telescope projects, or for other large projects involving both optics, mechanics, and electronics hard- and software. Next, we take a closer look at the principles of integrated modeling and, finally, we devote the rest of the chapter to more specific mathematical tools that form a basis for integrated modeling.

2.1 Systems Engineering and Integrated Modeling

Large telescope projects or large projects involving a mix of optical, mechanical and electronic systems, tend to become highly complex. It is often difficult to overlook the functionality of the complete system, so a systems engineering team plays an important role in such a project. It is the task of systems engineering to deal with matters related to global systems performance. In particular, systems engineering focuses on

- Global performance specifications
- Subsystem specifications
- Inter-system design trade-offs
- Error budgets
- Product tree definition
- Interfaces
- Configuration control and change management
- Documentation version control

In the best of worlds, systems engineering of large telescope projects should deal with the complete observatory, including performance seen by the end-user and the boundary conditions set by environment, logistics, community,

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etc. However, often, most emphasis is placed upon technical aspects of the telescope.

Design of a large optical telescope involves a variety of highly different tasks, such as design of structures and mechanisms, electric and electronic design, civil engineering, and software development. Systems engineering must span the entire design space and ensure that proper global trade-offs be done. Due to the complexity, computerized and graphical tools are applied for systems engineering. One example of a systems modeling language is "sysML" which is applicable both for system structure, behavior, requirement and parameter management.

In the future, new software packages will combine many of today's software design tools, for instance combining systems engineering, performance simulations, computational fluid dynamics, and finite element calculations. However, telescopes differ much from each other, and telescope technology is very special, so for telescopes, a change in design methodology is not nearby. Hence, within a foreseeable future, telescope designers must address performance simulation separately and the rest of the book is devoted to this task.

Until now, when dealing with the terms "system", "model" and "simulation", we have tacitly assumed these to be well-known. For the sake of completeness, we here quote from [1] definitions of the terms:

- A *system* is a combination of interacting elements organized to achieve one or more purposes. These "elements" in themselves may also be systems.
- A *model* is an abstraction of a system (simplified representation) based upon someone's perception of the system at some particular point in time or space, intended to promote understanding of the real system and/or to predict its performance and behaviour. Typically a model focuses on a specific aspect or aspects of a system at any one time.
- A *simulation* is the manipulation of a model (most likely a mathematical model) in such a way that it replicates the operation of a system in time and/or space to provide visual and/or data products to enable one to perceive the interactions and performance of the system that would not otherwise be apparent. Generally, a computerized version of a model is run over time to study implications of the interactions defined under various environmental conditions or external stimuli.

We are here dealing with mathematical models of large telescopes or complex combined optical, mechanical and electronic systems. Mathematical models are applied as a basis for performance calculations of various types, or for simulations in the time domain. The mathematical models are called "integrated models" because they describe a variety of subsystems, such as structures, optics, and control systems. Sometimes, the models are also referred to as *end-to-end models* and in many cases the two terms are used interchangeably although, strictly speaking, there is a difference between integrated models and end-to-end models. The term "integrated models" refers to a mix of technical disciplines and "end-to-end models" to a model of the system from input and boundary conditions to the end deliverable of the system as seen by the user.

Figure 2.1 depicts the typical interrelation between integrated models and the various technical disciplines involved in design of large telescopes or complex optical systems. The integrated model is formed using input or submodels from the structural and optical design, together with a first definition of the control system and environmental specifications, for instance concerning wind. There is generally an iteration process related to controller design, so that results from the integrated models are also applied for control system design. Results from the integrated model can be useful for setting up error budgets, and submodels can be applied for vibration analysis, for instrument design, for risk analysis and for evaluation and analysis related to the telescope science case. In general, integrated models of ground-based telescopes do not directly include thermal and earthquake effects although parts of integrated models are well suited for the purpose. The effects can also be efficiently studied by separate models within their respective disciplines.

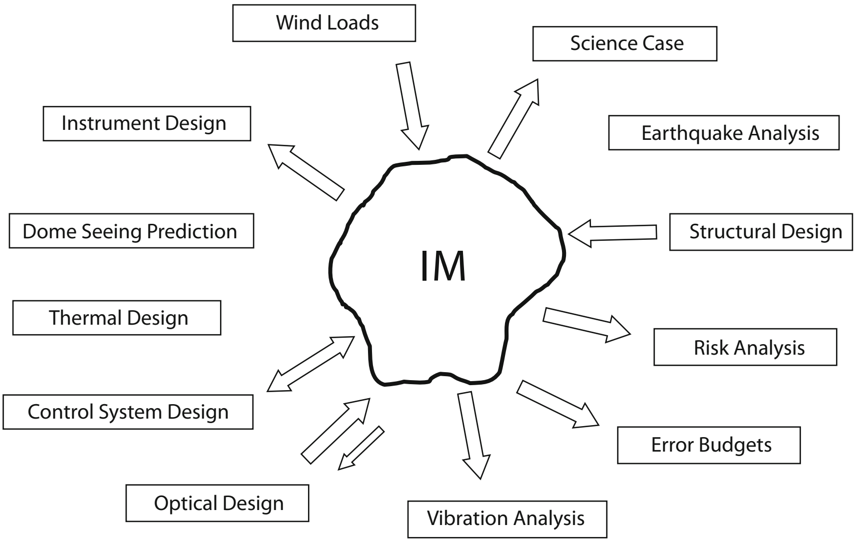

Fig. 2.1. Relationship between an integrated model (IM) of a large telescope and different technical disciplines used during the design process.

2.2 Integrated Modeling Objectives

Above, we have outlined the role of integrated modeling in relation to systems engineering and the general design process. Now, we will go into more depth regarding the composition of the models and the objectives of the modeling process [1–6].

An integrated model of a large, ground-based telescope may involve models of one or more of these subsystems:

- Optical sources
- Atmosphere
- Telescope optics
- Telescope structure
- Tracking and guiding control system
- Wavefront sensor(s)
- Adaptive optics
- Detectors
- Disturbance and noise sources
- Science Instruments
- Data pipe line and data analysis

Modeling of optical sources, data pipe line and data analysis is of high relevance for science case studies to study the scientific performance of the telescope and observatory. We shall here focus on the telescope system and the atmosphere beginning with the light waves arriving at the atmosphere and ending with the light reaching the final focus. We will later in this book describe sub-models for most of the subsystems involved in this light train and the disturbances that are relevant in the context.

There are several objectives for integrated modeling. Using interdisciplinary mathematical models, one may

- Determine the trade space and optimize the design
- Optimize performance
- Perform "what-if" investigations to study effect of excursions in trade-space
- Reduce project risk
- Perform sensitivity analysis and uncertainty modeling
- Study noise propagation in the system
- Provide confidence for project owners and participants
- Study the effect of changes
- Optimize error fixup for the system after erection

Reduction of project risk is of particular importance. The cost of new, large telescopes is so high and the telescope systems so complex, that it is imperative to create general confidence among the stakeholders that the system will work as intended. Hence, computer simulations are gaining more and more importance.

2.3 Modeling Concepts

Setting up and executing a model can potentially be performed in different ways. Before the advent of integrated modeling, one specialist would typically model the structure and hand over his results to an optical analyst that would determine the consequences of structural deflections. Also, the structural model might be handed over to a control engineer that would design the control loops. Ultimately all results would then be combined. Obviously such a process is tedious and it is one objective of integrated modeling to combine the various models.

One solution is to retain the individual software packages used by different specialists and orchestrate their execution. Data must then be transferred between the different software packages and the data must be reformatted to adapt to the individual packages. This approach has the advantage that the full functionality of the individual software modules is retained, which may lead to efficient execution. On the other hand, it also requires that the analyst masters the individual software packages in some detail or that different analysts be involved in the modeling.

It is generally more attractive to build the complete model in some suitable software environment. This avoids the drawbacks of the approach described above. However, in most cases the finite element model is not set up within the integrated model environment; finite element modeling is complex and computationally demanding, so it would call for an unreasonable programming burden.

Selection of an appropriate modeling environment is an issue of high importance. There are several dedicated modeling environments available, such as Modelica [7], Comsol Multiphysics®, Simulink®, and MATLAB®.

A typical concept for integrated modeling of a large, optical telescope is shown in Fig. 2.2. A finite element model is formulated for the structure using a dedicated general finite element program. Next, the model is exported to the integrated modeling environment. This model will generally be large and difficult to handle so a model reduction is performed, retaining the most essential features. Based upon an optical prescription of the telescope, ray tracing is performed to generate sensitivity matrices describing the consequences of angular or translational displacements of optical elements. Further, the actuators of the control system and of the various servomechanisms of the telescope are modeled in state-space form. Then, all of the models thus generated are combined into a large, joint, state-space model of the complete system.

Based upon the joint state-space model, the controllers of the servomechanisms and actuators can be modeled and their parameters can be optimized for the purpose of the model. At this point, a large state-space model describing closed-loop performance is available and can be analyzed using standard state-space tools on the basis of disturbance models and disturbance specifications.

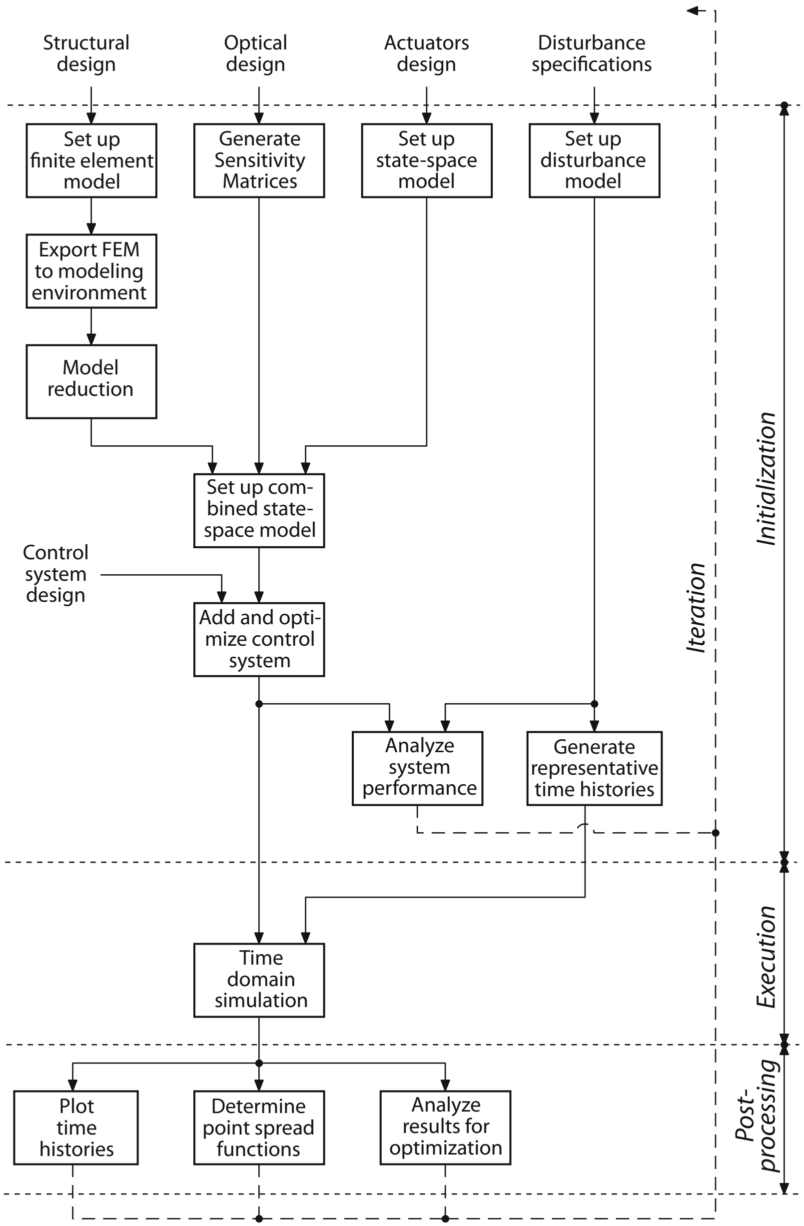

Fig. 2.2. Some typical steps for setting up and executing an integrated model of a telescope.

Then, using representative time histories of noise and disturbances, it is possible to simulate system performance in the time domain by solving a large set of ordinary differential equations. Although we have above assumed the models to be linear, it is at this stage entirely feasible to add non-linear features. For instance, certain wavefront sensor models are non-linear. Noise and disturbances may be either dynamical, for instance from wind and atmospheric turbulence, or quasi-static, such as from gravity and thermal loads. Also purely static effects, for example from fabrication errors, may be included.

On the basis of the time histories of the states found by solving the differential equations, the results can be analyzed, potentially leading to changes in the design parameters, and a new iteration step may commence.

More information on the overall approach for integrated modeling and the practical implementation is given in Sects. 12.1 and 12.2 on pp. 477–483.

When building a large, mathematical simulation model, it is highly important already from the start to consider approaches for validation of model correctness. This may be done by establishing test cases that can easily be compared to results from separate software packages or to measurements on systems already built. More information on this subject will be given in Sect. 12.6.

Above, we touched upon the possibility of applying either linear or non-linear models. Structures, telescope optics, and control systems can generally with reasonable accuracy be approximated by linear models. The advantage of using linear models is significant. All of the linear modeling tools of modern control engineering readily apply and many tools are much simpler for linear models. Hence, whenever possible, linear models should be used.

However, for certain subsystems, for instance wavefront sensors for which accurate models are needed, linear models will not suffice. Non-linear models are then needed and are entirely feasible, although they lead to some complications and normally also to longer computation times.

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