# 6 Formal Requirements Definition

### 6.5 System Engineering Tools

## Complex Tool Sets

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A more complex mission design effort will often make use of specialists who are able to effectively use engineering tools such programs for design and analysis of trajectories, optical systems, structures, mechanisms, and thermal and attitude control systems. Most of these software tools require dedicated and experienced specialists for the following reasons:

- The discipline knowledge that is embodied in most of these programs is itself quite complex. Just as one would not normally expect a mechanical engineer to design an optical system, so one should not expect anyone other than an experienced optical designer to make the most effective use of an sophisticated software tool for designing, simulating, and analyzing optical systems. It is not uncommon for users of such programs to have an MS or PhD in the related discipline
- The user interface to most of these programs is also quite complex. Something on the order of a year of dedicated experience is required to become proficient with such programs
- Due to the complexity and ongoing evolution of such programs, a user can lose significant proficiency as the result of just months of making either no use or even too little use of these tools
- It is very easy for these programs to produce unrealistic outputs with the wrong inputs. To be proficient, a user has to have enough knowledge of real, implemented systems to know when the output is useful or not. Beginning users should be paired with experienced ones
- High-end engineering design and analysis software can be quite expensive and typically includes ongoing fees for usage, technical support, and upgrades. For these programs to be cost-effective, it is often necessary to make continuing and heavy use of them. While less expensive, or even free versions of many of these programs can be found, their limited capabilities, the possibilities of no technical support and not having an experienced user, often outweigh their immediate savings

With the above understandings in mind, the more widely used types of engineering software include the following, which are presented in the order that they might be expected to be used on a project:

- **Optical System Design Tools, such as ZMAX and Code V.** It may seem illogical to begin the list of engineering tools with one that seems this specialized, but a large fraction (if not a majority) of space missions have optical observations as their primary goals. Lidar missions are based on optical observations, even though they have to generate the optical signal whose reflection is observed. A laser communications satellite needs to optically observe all of the laser terminals from which is it to receive data. X-ray, UV, IR, sub-millimeter and radio telescopes, including the receivers on space radar and spacecraft communication systems, are all fundamentally like optical telescopes, except that they operate in different ranges of the electromagnetic spectrum. It has been said that an astronomer begins the design of a new space telescope mission with the desired layout of the focal plane. Thus, optical system design tools, and their equivalents for other spectral ranges, are a logical place to start. Some example capabilities from such optical system design tools are ray-tracing, optimization, tolerancing, incorporation of the optical properties of lens and coating materials, diffractive effects, thermal analysis, polarization, scattering, stray-light analysis
- **Orbit simulation and visualization tools, such as STK.** These often come next because there is a desired orbit in space from which to perform a particular set of observations. However, reaching this orbit may not be practical. For instance, possibly undesirable, interfering zodiacal light does not completely disappear until one reaches the distance of Jupiter, but for now, this location is impractically expensive for space telescopes. It is not possible to make much more progress on mission design until an orbit can be picked for observations, and the observatory scoped to be compatible with both the environment of that orbit and the capabilities of an affordable launch vehicle to reach the orbit. Such orbit tools can support the design and visualization of orbits and trajectories that are Earth and Moon referenced, as well as interplanetary ones. Related capabilities includes those required for launch window determination, orbit maintenance, rendezvous and docking, gravity assist, orbit capture, and descent. Propulsion can be via finite burns (typically chemical) and continuous (typically electric)
- **The next step is often to determine the temperature distribution.** Which is often time varying over the full design and design the temperature

control system needed to maintain temperatures within the required operational and survival ranges. TSS and Thermal Desktop are example tools. Typically, these programs will need to know the overall geometry and materials of the observatory, the location and power of heat sources on the observatory, the orbit in which the observatory operates, and the expected timeline of the attitudes of the observatory. The design is broken into nodes and the software calculates internode radiation interchange data as well as incident and absorbed heat rate data originating from environmental radiant heat sources. Thermal analyzers also develop the capacitance and conductance network to account for conduction and thermal mass. Under time varying conditions, the analyzers will repeat these solutions over sufficiently small time increments to get a sufficiently accurate time history of the temperature distribution. This information will provide the basis for adding the required heaters, insulators, radiators and coatings to the design to keep temperatures within their required ranges. Sometimes active temperature control, consisting of coolers, temperature sensor and control software will need to be added to the design

The reason for placing structural analysis after thermal analysis is that a frequent goal of FEA is to determine distortions and stresses resulting from the effects of materials CTE and temperature changes. Structural analysis is typically performed using Finite Element Analysis (FEA), using programs such as NASTRAN. The basic approach is to discretize an overall complex structure into a number of small structural elements, each of which has a readily model-able structural behavior. This assemblage of elements is combined into a global stiffness matrix to which loads are applied, yielding stresses and stains for each of the structural elements.

In addition to the engineering analysis tools mentioned above, a significant number of utilities are required to use them effectively. Primary are the so-called mesh-generators that can automatically (or nearly so) generate a mesh of thousands of finite elements from a 3D CAD representation of a single complex structure. Similar mesh generators exist for thermal analyzers. Often separate utility programs will provide 3D graphic representations of the analysis outputs of thermal and structural analyzers. Color can be used to show areas of different temperatures and stresses, and sometime structural distortions are displayed by multiplying the distortions by a large enough factor that it becomes visually very apparent.

**Type of Software: Computer Aided Design (CAD)**

For purposes of clarity, the term CAD is used here to describe software tools for the design, definition and communication of the geometric elements of a space system, typically a spacecraft, but also possibly a rover, space-station or LV. This type of CAD is sometimes referred to as mechanical CAD or MCAD, to differentiate it from other kinds of CAD, like electrical CAD (ECAD) for circuit design.

From the perspective of space mission designers and developers, it is useful to discriminate between two uses of CAD, concept development and product development. Although there is not a precisely defined dividing line, CAD for concept development tends to be limited to the definition and display of the main pieces of a space system, such as main structure, solar arrays, and electronic boxes.

Because CAD systems for concept design tend to be simpler than those for product design, a space mission designer, such as a systems engineer, could make effective occasional use of such software to help define a space system in the early phases of developing a space mission. With about a week of self-instruction, an occasional CAD user, such as a PI or SE, should be able to effectively use a relatively simple concept development CAD program to build simple 3D models of concepts for space systems, generate images useful for communicating the concepts, and output STEP files so that others can make use of the conceptual 3D geometry.

However, it is probably more usual that a dedicated CAD operator will be used for conceptual design. This is because conceptual CAD systems, though they have a less complex UI than product CAD, can still be quite complex, and a dedicated user will be usually be significantly more capable and productive.

By contrast, product development CAD is typically more complex and intended to be able to not only represent every detail (e.g., down to individual fasteners and connectors) of every component of a very complex design, but also to provide all of the geometric data and detailed drawings required to actually manufacture and assemble the physical system. Product development CAD systems, given their wider range of capabilities and consequently more complex UI, can take on the order of a year to master, and they pretty much require that the operator continue to use them full time to maintain an high enough level of proficiency to justify their cost. It should be noted that a 3D CAD system for product development often effectively serves as the foundational engineering software tool for the design, definition, analysis and fabrication of the overall flight system, as well as many of its individual components.

Because CAD systems can contain a complete definition of the geometry and materials of a space system and can derive information from these data, they can also provide capabilities that go beyond the definition and display of geometry. Table 6web-1 illustrates a representative range of capabilities that can be found in CAD system and indicates which of which of these might be found in concept and product type CAD systems.

As shown in Table 6web-2, a number of CAD vendors provide both types of CAD software.

A license for a typical conceptual design CAD system might be in the range of $5K with about $1K/yr for support and upgrades. A high end product CAD system license will cost about $20K plus about $5K/year for support and upgrades. Laptop computers are normally adequate to run either type of CAD. However, a lead product CAD user who is in charge of integrating the inputs of multiple subsystem CAD users for the overall definition of a complex space system may well need a high-power desktop workstation to effectively work with the resulting very large data base.

In closing, it should be noted that there is no reason in principle why a CAD system could not incorporate all of the capabilities of all other engineering software (such as thermal and structural analyzers), and in fact much work has been done along these lines. To date, the major barrier has been that a single person lacks the discipline knowledge to make effective use of these other tools. However, in time, enough parametric rules could be incorporated into CAD systems that a single user could make some effective use of these more specialized analytical capabilities.

**Table 6web-1. Representative Major Capabilities of CAD Programs.**

| C | P | T | CAPABILITY |
|---|---|---|---|
| √ | √ | *I* | STEP and IGES Files for data exchange |
| √ | √ | *I* | Input (again often via STEP files) of specialized 3D geometric information, such as the shapes and relative positions of the mirrors and lenses that constitute an optical system. |
| | √ | *I* | 3 D operator input using 3D mouse |
| | √ | *I* | Databases for managing efforts of multiple CAD operators |
| √ | √ | *G* | Development of 2D and 3D geometries |
| | √ | *G* | Use of Non-Uniform Rational Basis Splines (NURBS) to provide a single mathematical definition to develop, represent and modify a wide range of conic and splined curves and surfaces |
| √ | √ | *G* | Use of Boolean operators of union, intersection and difference to define more complex solids from simpler solids |
| √ | √ | *G* | Definition of subassemblies which can be used hierarchically to define more complex assemblies |
| √ | √ | *G* | Assignment of material properties (type of material, density, color, etc) to individual CAD objects |
| | √ | *G* | Calculation of geometric properties (such as surface area, volume, mass, center of gravity, mass moments of inertia) for arbitrarily complex structures |
| | √ | *G* | Definition of motions and interactions of mechanism |
| | √ | *G* | Checking for both static and dynamic interferences, as well as FOV interferences |
| | √ | *G* | Determining and defining manufacturing tolerances |
| √ | √ | *D* | Color or black and white displays of 3D objects with orthogonal, isometric and perspective projections |
| √ | √ | *D* | Displays with hidden line and hidden surface removal |
| | √ | *D* | Displays with ray-tracing to shows shadowing, reflections, etc |
| √ | √ | *D* | Ability to make selected items invisible or translucent |
| √ | √ | *D* | Cross-section views |
| √ | √ | *D* | Animated displays to illustrate the operation of mechanisms |
| √ | √ | *O* | STEP and IGES Files |
| √ | √ | *O* | PDF Files |
| | √ | *O* | SLA Files for rapid prototyping processes such as Stereo-lithography |
| | √ | *O* | Movie files to show mechanism operations |
| √ | √ | *O* | Spreadsheet format Master Equipment List (MEL) with the identification of individual parts and their masses, along with the identification of subassemblies and their subtotal masses. |
| | √ | *O* | Provision of 3D geometric information (often via files using the STEP data-exchange format) for thermal analysis, structural analysis, and manufacturing. |
| | √ | *O* | "Shrink wrap" geometry that only represent the visible outer surface geometry, for instance of a satellite to be used in an orbit simulator to help design and visualize maneuvers. |

C=Concept CAD, P=Product CAD, T= Type of Capability "T" Column Entries: I=Input, G=Geometry Definition, D=Display, O=Output

**Table 6web-2. Representative CAD Programs, Intended Use, Vendor and Website.**

| Name of Program | Intended Use | Vendor | Website |
|---|---|---|---|
| ***AutoCAD & Autodesk*** | Concept & Product | Autodesk, Inc. | http://usa.autodesk.com/ |
| ***CATIA (Computer Aided Three-dimensional Interactive Application)*** | Product | Dassault Systemes | http://www.3ds.com |
| ***SolidWorks*** | Concept | Dassault Systemes | http://www.3ds.com |
| ***Creo Elements/Pro (formerly known as Pro/ENGINEER)*** | Product | Parametric Technology Corporation (PTC) | http://www.ptc.com |
| ***Creo Elements/Direct (formerly CoCreate)*** | Concept | Parametric Technology Corporation (PTC) | http://www.ptc.com |
| ***NX CAD (evolved from Unigraphics)*** | Product | Siemens PLM Software | http://www.plm.automation.siemens.com/en_us/ |
| ***Solid Edge*** | Concept | Siemens PLM Software | http://www.plm.automation.siemens.com/en_us/ |