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Pengfei Duan

Wenping Lei

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On the collaborative design and simulation of Space Camera: STOP Structural/Thermal/Optical) analysis

Duan Pengfei
Beijing Institute of Space Mechanics and Electricity
Beijing, P. R. China

Lei Wenping
Beijing Institute of Space Mechanics and Electricity
Beijing, P. R. China

Abstract—**A number of disciplines (mechanics, structures, thermal, and optics) are needed to design and build Space Camera. Separate design models are normally constructed by each discipline CAD/CAE tools. Design and analysis is conducted largely in parallel subject to requirements that have been levied on each discipline, and technical interaction between the different disciplines is limited and infrequent. As a result a unified view of the Space Camera design across discipline boundaries is not directly possible in the approach above, and generating one would require a large manual, and error-prone process.**

A collaborative environment that is built on abstract model and performance template allows engineering data and CAD/CAE results to be shared across above discipline boundaries within a common interface, so that it can help to attain speedy multivariate design and directly evaluate optical performance under environment loadings.

A small interdisciplinary engineering team from Beijing Institute of Space Mechanics and Electricity has recently conducted a Structural/Thermal/Optical (STOP) analysis of a space camera with this collaborative environment. STOP analysis evaluates the changes in image quality that arise from the structural deformations when the thermal environment of the camera changes throughout its orbit. STOP analyses were conducted for four different test conditions applied during final thermal vacuum (TVAC) testing of the payload on the ground.

The STOP Simulation Process begins with importing an integrated CAD model of the camera geometry into the collaborative environment, within which 1. Independent thermal and structural meshes are generated. 2. The thermal mesh and relevant engineering data for material properties and thermal boundary conditions are then used to compute temperature distributions at nodal points in both the thermal and structures mesh through Thermal Desktop, a COTS thermal design and analysis code. 3. Thermally induced structural deformations of the camera are then evaluated in Nastran, an industry standard code for structural design and analysis. 4. Thermal and structural results are next imported into SigFit, another COTS tool that computes deformation and best fit rigid body displacements for the optical surfaces. 5. SigFit creates a modified optical prescription that is imported into CODE V for evaluation of optical performance impacts.

The integrated STOP analysis was validated using TVAC test data. For the four different TVAC tests, the relative errors between simulation and test data of measuring points temperatures were almost around 5%, while in some test conditions, they were even much lower to 1%. As to image quality MTF, relative error between simulation and test was 8.3% in the worst condition, others were all below 5%.

Through the validation, it has been approved that the collaborative design and simulation environment can achieved the integrated STOP analysis of Space Camera efficiently. And further, the collaborative environment allows an interdisciplinary analysis that formerly might take several months to perform to be completed in two or three weeks, which is very adaptive to scheme demonstration of projects in earlier stages.

Keywords- collaborative design and simulation environment, abstract model, performance template, STOP integrated analysis

I. INTRODUCTION

A number of disciplines (mechanics, structures, thermal, and optics) are needed to design and build Space Camera [1]. Separate design models are normally constructed by each discipline CAD/CAE tools. Design and analysis is conducted largely in parallel subject to requirements that have been levied on each discipline, and technical interaction between the different disciplines is limited and infrequent. Access to engineering results is largely limited to discipline specialists because of the level of education and experience needed to understand the technical issue, terminology, and computer tools needed to do discipline work.

As a result a unified view of the Space Camera design across discipline boundaries is not directly possible in the approach above, and generating one would require a large manual, and error-prone process. For these reasons, the discovery of camera-level design issue tends to occur late in the design process, often after the hardware has already been built. Late discovery of design issue, when they are far more time consuming and expensive to fix, has been identified as a key contributor to the rise in on-orbit failure and large cost and schedule overruns that currently affect most of the space camera programs.

II. A COLLABORATIVE SPACE CAMERA DESIGN AND SIMULATION ENVIRONMENT

A collaborative environment that is built on abstract model and performance template allows engineering data and CAD/CAE results to be shared across above discipline boundaries within a common interface, so that it can help to attain speedy multivariate design and directly evaluate optical performance under environment loadings [2].

The collaborative workspace is based on an ontologically-derived data model and was designed to achieve many of the goals listed above, providing design teams with a environment that supports concurrent engineering for the design of optical devices.

The fundamental technology that underlies the framework is Abstract Engineering Model (AEM™) [3]. The AEM is a common, highly-extensible CAE data model that is based on a comprehensive ontology for the domain, Simulation for Product Development. The AEM is the blueprint that defines how data is represented, the relationships between them, and the axioms that govern their collective behavior. The AEM on Space Camera STOP Analysis is shown in Figure 1.

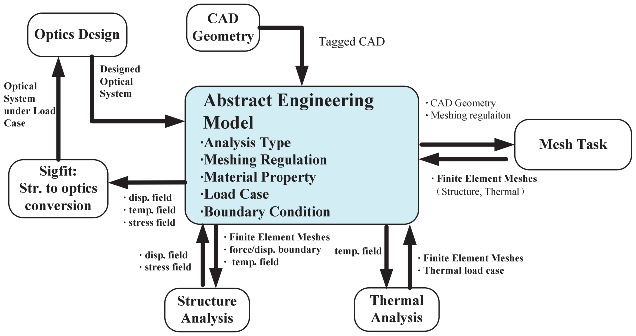


Figure 1. Abstract Engineering Model on Space Camera STOP Analysis

The geometry prepared by the CAD engineer is tagged so that the subset of the overall model of interest for downstream STOP analysis is identified, the optical surfaces that match the named surfaces in the optical model is identified, and also material names of the parts and optical surface treatment names of various surfaces are specified.

Today's space camera program impedes the ability of teams to explore multiple concepts in the time and budget available. For each new concept, most of the downstream simulation work must be repeated, at great cost, often making it impractical to explore many concepts. The collaborative design and simulation workspace aims to capture the essence of the engineering problem being solved, without needing CAD geometry. This is captured in a simulation template, where geometry is considered an input to the design being simulated, no different than say, material properties or loads. The ability to reuse simulation templates would allow multiple, geometrically different concepts to be simulated with little or no additional downstream engineering data reentry – the essential engineering problem is defined once and reused for each concept. The ability to evaluate many more concepts would ensure a better final design within the time and budget available.

Incremental changes to the design, geometric or otherwise, must be almost trivial to make and then to simulate. Automatic tools to explore the design space must also be provided as an integral part of the environment and the data. The various, inefficient, manual and error-prone steps required by existing tools must be eliminated.

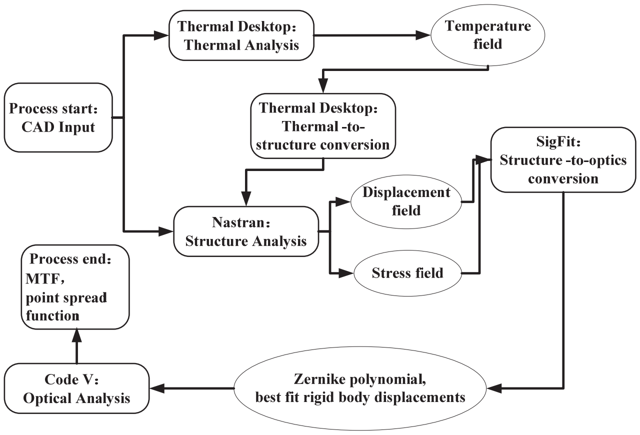


Figure 2. Performance Templates on the Space Camera STOP Analysis

Performance templates, as Figure 2 shows, facilitate the capture of simulation expertise and can be reused by design engineers. With these templates, experts and design engineers alike can perform more complex simulations earlier in the design, with greater confidence in the accuracy of these simulations. In addition, the Abstract Modeling technology allows these templates to be completely specified before CAD geometry becomes available. The essence of the engineering problem being solved is captured, without an undue emphasis on a particular version of the geometry – the geometry is treated as just one of many characteristics of a design. The experts' rules of thumb can be specified and enforced easily. Abstract Modeling also makes it possible to evaluate multiple concepts effectively, with little or no engineering data reentry for the simulation of each concept, even if its geometry is significantly different.

III. INTEGRATED STRUCTURAL/THERMAL/OPTICAL (STOP) ANALYSIS

A small interdisciplinary engineering team from Beijing Institute of Space Mechanics and Electricity has recently conducted a Structural/Thermal/Optical (STOP) analysis of a space camera with this collaborative environment. STOP analysis evaluates the changes in image quality that arise from the structural deformations when the thermal environment of the camera changes throughout its orbit. STOP analyses were conducted for four different test conditions applied during final thermal vacuum (TVAC) testing of the payload on the ground.

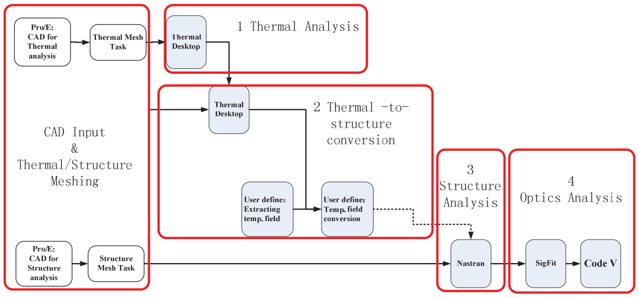


Figure 3. Integrated STOP simulation process

The simulation process, shown in Figure 3, was used to conduct the integrated STOP assessment of the contractor's focus control method.

The STOP Simulation Process begins with importing a single integrated CAD model of the instrument geometry into the process environment. Independent thermal and structural meshes are then generated. The thermal mesh and relevant engineering data for material properties and thermal boundary conditions are used to compute temperature distributions at nodal points in both the thermal and structures mesh within Thermal Desktop (http://www.crtech.com), a COTS thermal design and analysis code. Thermally induced structural deformations of the metering structure and optical components are then evaluated in Nastran (http://www.msc.com), an industry standard code for structural design and analysis. Thermal and structural results are next imported into SigFit (http://www.sigmadyne.com), another COTS tool that computes best fit rigid body displacements for the optical surfaces and Zernike polynomial representations for wavefront errors introduced by the deformations of the reflecting mirror surface figures. SigFit creates a modified mirrors subassembly optical prescription that is imported into CODE V (http://www.opticalres.com) for evaluation of optical performance impacts. Some more detail on each of these process steps is given below.

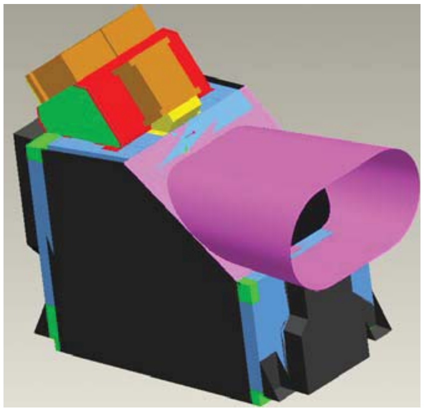
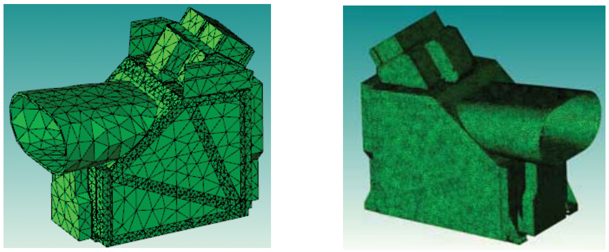


Figure 4. CAD model of the space camera

The STOP process begins by importing a single integrated CAD model for the space camera assembly into the mechanical CAD application, Pro/E (http://www.ptc.com). Tags are applied by discipline engineers to the parts, faces, and subassemblies that they will use for downstream analysis. Tags are used to apply a variety of properties to the CAD model and to reapply those properties when either they or the CAD model itself are changed as trade studies or design alternatives are explored, as Figure 4 shows. CAD geometry is tagged to group parts for meshing, set meshing parameters, identify optical surfaces, and associate material properties and surface treatments with parts and surfaces.



Thermal mesh Structure mesh

Figure 5. Thermal and Structure analysis meshes

After the CAD model is imported and tagged, the thermal and structures engineers develop Finite Element Meshes (FEM) for the parts of the CAD model that are of interest to them for subsequent analysis, Figure 5 shows. Meshing parameters are developed and iteratively refined by each discipline to produce computationally efficient yet stable results, and these parameters are captured for re-use at each stage of design evolution within the collaborative environment.

The thermal model consists of the thermal mesh for the system geometry plus all of the conditions and properties needed to evaluate the distribution of temperatures across the optical system. The thermal and optical properties of all materials, heater power levels, boundary condition temperatures, and conductances between the various components that make up the thermal model are all specified within an engineering data model in the collaborative environment. This data model is, among other things, a database of engineering data for all of the engineering disciplines that can be shared and re-used by any of the underlying applications. For any given TVAC test condition of interest, the above thermal model parameters are passed to Thermal Desktop for computation of temperatures at each node on the thermal mesh. Thermal Desktop is also used to map these temperatures onto the nodes in the structures mesh.

Similarly, the structures model consists of the structures mesh for the system geometry plus all of the conditions and properties needed to evaluate the structural deformations produced in response to the temperature field calculated by Thermal Desktop. The structural properties of all materials, boundary conditions, and assumptions about the types and parameters of structural contact between components are specified in the abstract data model. These parameters and the structures mesh are passed to Nastran for computation of displacements of each node in the structures mesh.

The temperatures and displacements at the nodes on the structural mesh are passed to a pair of SigFit tasks. SigFit tasks computes the best fit rigid body displacements and tip/tilt of each mirrors surface and a set of Zernike polynomials that represents the aperture-dependent mirrors surface deformations, including radius of curvature change, for each surface. SigFit uses this information to generate a modified mirrors design sequence file that it passes to CODE V for subsequent analysis of optical performance impacts. For the purposes of this STOP analysis, the thermally distorted M1-4 (show in Figure 6) CODE V prescription was analyzed to look for changes in visible channel image quality and focus.

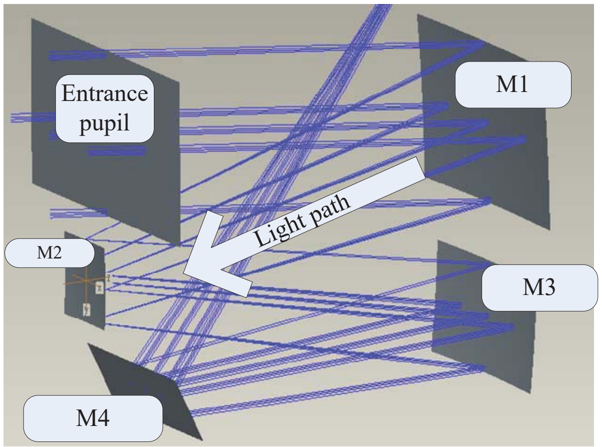
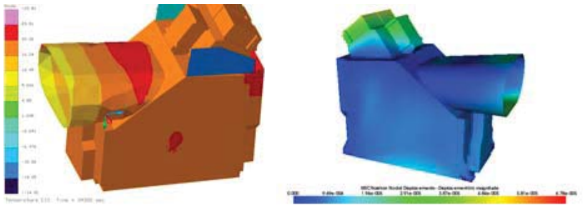


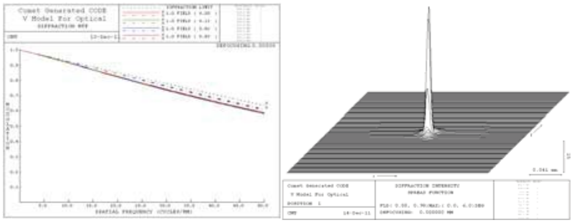
Figure 6. Optical mirror surfaces model

The engineers begin performing scoping calculations to better understand the thermal and structural responses of the space camera system, Figure 7 shows the temperature field and displacement field of the space camera under a certain transient environment loading, and Figure 8 shows the subsequent optical index.



Temperature field displacement field

Figure 7. Temp. field and disp. field of the space camera on the given on-orbit time



MTF point spread function

Figure 8. MTF and point spread function of the optical system on the given time

IV. VALIDATION OF THE INTEGRATED STOP MODEL

The simulation model developed for our integrated STOP analysis was validated using test data from the special test configuration

The thermal model was validated using TVAC test data. For this test, an engineering model with M1-4 mirrors was instrumented with extra thermistors and subjected to thermal soak and thermal transient tests while mounted by three stainless steel standoffs inside of a thermal vacuum chamber.

A comparison of our model predictions to measured thermistor data at all available monitoring points for a thermal soak test condition is given in Table Ⅰ. Results correlate very well with test data for most thermocouples. Predictions for M2 are higher than test results by error of more than 5%. The largest (11.5%) discrepancy is in part due to a questionable test data reading, as the temperature deviation of the mirror should never be larger than1.5℃ in test condition. Some of the M2 model predictions may be in error due to the fidelity of our model of the support structure used for this test (standoff feet, etc.).

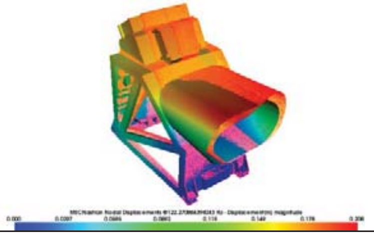
TABLE I. TVAC TEST COMPARISONS

Test Case			**M1**	**M2**	**M3**	**M4**
Case 1：low temperature(L. T.) loop	**L. T. transient state**	**Test Data（℃）**	19.71	17.64	20.67	19.35
		Simulation（℃）	19.93	19.67	19.74	19.55
		Error	1.1%	11.5%	5.1%	1.0%
	H. T. transient state	**Test Data（℃）**	19.99	19.05	20.84	19.88
		Simulation（℃）	20.03	19.78	19.77	19.57
		Error	0.2%	3.8%	5.1%	1.6%
Case 2：high temperature(H. T.) loop	**L. T. transient state**	**Test Data（℃）**	20.20	19.66	20.7	20.3
		Simulation（℃）	20.12	20.48	20.49	21.10
		Error	0.4%	4.17%	1.02%	3.9%
	H. T. transient state	**Test Data（℃）**	20.40	19.74	20.8	20.38
		Simulation（℃）	20.18	20.60	20.53	21.18
		Error	1.1%	4.35%	1.32%	3.9%

The structure model was validated using vibration test data. Similarly, the engineering model with M1-4 mirrors was instrumented with acceleration transducers and mounted on a 25t vibration test stand.

A comparison of our model predictions to measured acceleration transducer data for the vibration test condition is given in Table 2.

TABLE II. VIBRATION TEST COMPARISONS

	Test Data	**Simulation**	**remarks**
Natural frequency	119HZ	122.3 HZ	Error：2.7%
Natural frequency model	Swing motion		Correspondence match

According to Table Ⅱ, our structure model dynamics character predictions were in excellent agreement with measured result.

TABLE III. MTF TEST COMPARISONS

Cases		**MTF of certain spectral coverage**		
		Test Data	**Simulation**	**Errors**
Case 1：low temperature loop	**L. T. transient state**	0.25	0.26	4%
	H. T. transient state	0.24	0.26	8.3%
Case 2：high temperature loop	**L. T. transient state**	0.24	0.23	4.35%
	H. T. transient state	0.24	0.25	4.17%

As to the final evaluation of the space camera character, image quality MTF, as Table Ⅲ shows, relative error between simulation and test was 8.3% in the worst condition, others were all below 5%.

Through the validation, it has been approved that the collaborative design and simulation environment can achieved the integrated STOP analysis of Space Camera efficiently. And further, the collaborative environment allows an interdisciplinary analysis that formerly might take several months to perform to be completed in two or three weeks, which is very adaptive to scheme demonstration of projects in earlier stages.

V. CONCLUSION REMARKS

The collaborative performance engineering workspace supports the core requirement of the concurrent engineering process – the need for highly qualified, cognizant teams to be able to work closely together, sharing data, evaluating the progress of the design, and exploring various design options rapidly, without being unduly constrained by the artificial limitations and boundaries of the underlying CAD and CAE tools.

The collaborative workspace, with the underlying AEM, provides an implementation of an ontologically-based CAE data model and has begun to fundamentally change the paradigm for simulation in product design – this is a lot closer to realizing true simulation-driven concurrent engineering.

Towards simulation-driven concurrent engineering, the key lessons learned from the session described above are:

A. Supporting a concurrent engineering process

Engineers work more collaboratively throughout the process. The individual domain experts gain a better understanding of all aspects of the overall system. Work is immediately and effortlessly shared in 3-D form without the need to run all the CAD and CAE tools. Analysis results are immediately available for review and downstream use.

B. Achieving performance-driven engineering

Key performance requirements take center stage. At any time, for each version of the design, these data can be reviewed by the entire team without the need to run the underlying CAD and CAE tools.

C. Reusing templates

Expertise developed by the entire team on a particular product is captured and reused in templates. The reuse of templates significantly reduces manual steps and related errors, while ensuring higher quality, more accurate and repeatable simulations. The effect that a particular engineer’s changes can have on the key performance requirements of the product is assessed rapidly.

D. Using a single, consistent data model for all the data in a project

The data are well organized and easily accessible across the entire Project. For example, there is never any doubt which version of the CAD model was used for simulations performed in a particular Stage. The history of all the significant versions of the CAD and CAE models and all the analyses that were performed is maintained without effort.

E. Reducing errors and wasted effort due to data translation

Data are not translated from one format to the other, but maintained within a single consistent form that is mostly independent of the underlying CAD and CAE tools.

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