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Automated Multidisciplinary Optimization of a Space-based Telescope

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ABSTRACT

Automated design space exploration was implemented and demonstrated in the form of the multidisciplinary optimization of the design of a space-based telescope.

Off-the-shelf software representing the industry standards for thermal, structural, and optical analysis were employed. The integrated thermal/structural/optical models were collected and tasked with finding an optimum design using yet another off-the-shelf program. Using this integrated tool, the minimum mass thermal/structural design was found that directly satisfied optical performance requirements without relying on derived requirements such as isothermality and mechanical stability. Overdesign was therefore avoided, and engineering productivity was greatly improved.

This ambitious project was intended to be a pathfinder for integrated design activities. Therefore, difficulties and lessons learned are presented, along with recommendations for future investigations.

INTRODUCTION: PROBLEM STATEMENT

Structural, thermal, and optical engineers typically work independently of each other using unrelated tools, models, and methods. Without the ability to rapidly exchange design data and predicted performance, and therefore to influence each other's efforts, the prior state-of-the-art for the design of advanced optical systems was inadequate: it has henceforth resisted attempts to achieve the ideals of concurrent engineering. Limited success has been achieved at a very top-level (suitable for conceptual design studies), but only by approximating or neglecting the detailed design tasks that the engineering specialist must perform in later mission phases.

Without the ability to work concurrently, the disciplines of thermal control, structures, and optics levy worst-case performance requirements on each other such that each specialty can contribute to a design independently. The optical engineers dictate physical distortion limits to the structural engineer, who then dictates limits on temperatures and gradients to the thermal engineer. Requirements are derived, then flowed down. The thermal and structural engineers blindly obey these limits under all operational conditions, thereby satisfying the optical performance requirements.

That approach results in a stack-up of margins and inevitably to over-design, to the point of rendering advanced missions such as NASA's Next Generation Space Telescope (NGST), with its cryogenic large aperture optics, difficult to achieve without an integrated design approach. For example, temperature gradients in a mirror support structure are inconsequential as long as the required optical performance is achieved, yet *derived* limits on such gradients often become a design driver for thermal control specialists.

Reference 1 describes the implementation of a prerequisite step: the systematic identification and elimination of bottlenecks for the integrated thermal/structural/optical design evaluation. Automated communication pathways were established between ORA's CODE V® optical software, the MSC/NASTRAN® structural analyzer, and C&R's SINDA/FLUINT and Thermal Desktop thermal design system. These pathways allowed independently built models in each of these programs to accurately exchange data with each other.

For example, C&R Thermal Desktop can be used to map and export temperatures to MSC/NASTRAN, and a standalone program called Sigmadyne's NASCODE is used to convert NASTRAN deflections into surface motions of optical components in the CODE V model. Thus, a turnkey method was established to evaluate the optical performance of a candidate thermal/structural design.

AUTOMATED DESIGN SPACE SEARCHING

This paper describes the integration into a system (OptiOpt™) that autonomously searches for optimum designs using iterated analytical evaluations of candidate designs.

Using the preparatory developments described in Reference 1, a top-level multidisciplinary design optimization (MDO) environment was chosen: Engineous' iSIGHT® (Ref 2). This software allows the user to define top-level design variables, objectives, and constraints, and to develop a complex design evaluation procedure that involves multiple, stand-alone software programs. iSIGHT includes several varieties of optimization methods. iSIGHT also includes other parametric analysis engines that were not exercised in this project (such as reliability assessments, Design of Experiments, Six Sigma robust design, etc.), but it should be noted that they are immediately available as easily as optimization. In other words, the hard work (code integration) has been completed, and iterative point design evaluations can be applied to many other engineering tasks.

However, most of the development in this project was independent of the iSIGHT selection, and could be reapplied with minimal effort to any of the other multidisciplinary design analysis/optimization (MDA/MDO) codes available (see "Future Work" below), or even to custom design processes.

CONNECTIONS TO THE MDO ENVIRONMENT

This section describes the means with which each of the analysis codes was linked into the iSIGHT, the MDO environment chosen for OptiOpt, design evaluation process.

NASTRAN and NASCODE were both linked to iSIGHT using nonintimate connections. In other words, the input files for these programs were modified by iSIGHT, the programs were run in batch mode, then their output files were read by iSIGHT.

Despite the creation of an API for CODE V by ORA in support of this project (Ref 1), a nonintimate connection (namely, a text file read/write interface) was also used to link that code as well for the demonstration problem, in part because CODE V can easily be run in a batch mode invoking predetermined macros with little overhead cost.

SINDA/FLUINT and Thermal Desktop, on the other hand, required special treatment: a "persistent" (active, waiting) and more intimate connection. The reasons for this special treatment include:

- Thermal Desktop does not have a batch mode nor does it use text files. It can, however, launch a SINDA/FLUINT run and be commanded by that run.
- Starting Thermal Desktop requires loading up a CAD drawing, which is fast for a single time, but wastes time if done tens or hundreds of times needlessly.
- SINDA/FLUINT requires significant overhead to restart it. In addition to full preprocessing of all inputs with each execution, it invokes a Fortran compiler to enable user logic, essentially recreating a custom program with each execution. This would be prohibitively slow if a SINDA/FLUINT run had to be restarted for each iteration of a multidisciplinary design evaluation.
- SINDA/FLUINT steady state runs are inexpensive if they start from close initial conditions assuming the results of the last run are still available as a starting point. Since steady state analysis comprise most design evaluation procedures, this can be a significant speed enhancement.
- iSIGHT parsing is slow, while SINDA/FLUINT users can include file I/O instructions as part of their model. The slow parsing speeds were tolerable for NASTRAN and CODE V because reduced input/output files were used. Reduced files could also have been used for SINDA/FLUINT, but that would have placed a slight burden on the end user.

A "named value" method was employed, wherein iSIGHT and SINDA open and close small files written in a simple iSIGHT-dictated format. This is very easy for end users to do, and could be facilitated even more by creating new SINDA/FLUINT options should the need arise. The only disadvantage of this method is that the SINDA/FLUINT user must know the equivalent names of the pertinent variables in iSIGHT if they are different from the parametric "register" names used in SINDA/FLUINT.

Persistence, or the ability to start SINDA/FLUINT and Thermal Desktop once and then leave them waiting until their turn comes around again, was critically important as noted in the above listed arguments. To enable persistence, a third code, iSINDA, was created. The user invokes the iSIGHT connection within the SINDA/FLUINT input file, providing either the PROCEDURE or the RELPROCEDURE as an iterative "routine" to be invoked every time iSIGHT requires a thermal evaluation. Although this functionality was not required by OptiOpt, it represented a first "simple" step and allows thermal engineers to use iSIGHT and SINDA/FLUINT without Thermal Desktop.

Alternatively, iSINDA can be started using a Thermal Desktop drawing file. This usage invokes Thermal Desktop first, which then launches SINDA/FLUINT in a dynamic mode, which in turn communicates with iSIGHT using named value files. When the user exits iSIGHT, SINDA/FLUINT is terminated and its clean-up operations (if any) are performed, and the connection with Thermal Desktop is closed. (Thermal Desktop, however, remains open such that the user has the choice of whether or not to accept the final answers.)

DEMONSTRATION PROBLEM

In order to test the final suite of codes and to demonstrate OptiOpt, a space-based telescope design was weight optimized. This section briefly describes the telescope design, the math models based upon it, the optimization task, and final results.

TELESCOPE DESCRIPTION

A simplified space-based telescope was selected as a starting point. This room-temperature choice (the detector is at 68°F) was made due to the lack of availability of a suitable cryogenic design. A cryogenic telescope would have provided more stressing thermoelastic deflection examples, but as will be shown below an alternate room temperature design was investigated specifically to exercise this capability of OptiOpt.

MODEL DESCRIPTIONS

Structural Model--A full finite element MSC/NASTRAN® model was built, but for viewing purposes a cut-away plot is shown in Figure 1.

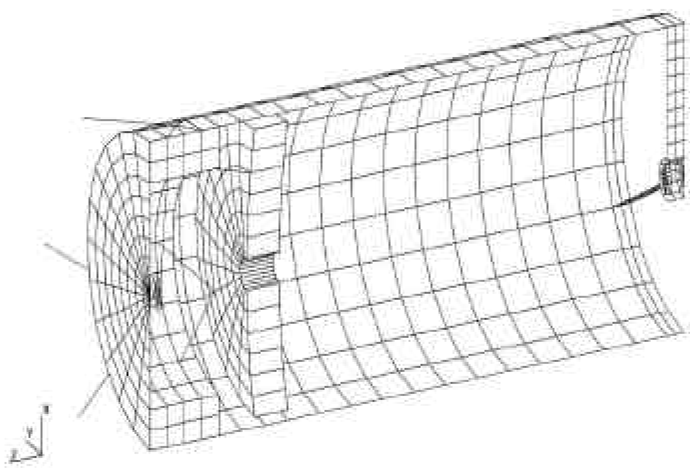

Figure 1: Cut-away View of NASTRAN Model

The primary mirror (PM) is represented as a 3D equivalent stiffness model. In a 3D equivalent model, the face plates are modeled as plates of proper thickness, but the lightweight (egg-crate) core is modeled as solids with reduced modulus and density. This provides greater flexibility during the optimization phase to allow egg-crate properties such as cell size and wall thickness to vary without remodeling.

The primary mirror mounts are represented as 6 struts grouped in 3 bi-pod pairs. The strut design is governed by a trade-off between stiff members required for high natural frequency and soft members required to isolate the delicate mirror from the remaining structure.

The secondary mirror (SM) is solid ULE material and is represented by solid elements. It is supported by 3 thin plate-like flexures which have the same conflicting requirements as the PM mounts.

The secondary mirror spider design is also governed by conflicting requirements to be stiff for the high natural frequency requirements, yet be narrow so that light obscuration is minimal. The focal plane (FP) is also supported by a spider assembly with the same conflicting requirements.

The remaining structure is the metering shell, main mount ring, and main mount struts. These are standard structural elements with conventional design trades of minimal weight verses high natural frequency and allowable stress.

Structural cases include launch stresses as well as on-orbit thermoelastic distortions. Buckling analyses were neglected.

Thermal Model--A thermal model was built using Thermal Desktop and SINDA/FLUINT. Note that this model was built independently of the NASTRAN structural model described above, but it is still able to export temperatures to that dissimilar model without introducing artificial distortions.

Figure 2 displays an external view of the telescope and associated spacecraft bus. The spider supports holding the secondary mirror are visible in the aperture. Note that items such as solar panels and doors exist in the thermal model but not the structural model. These surfaces are critical for correct radiation exchange with the environment.

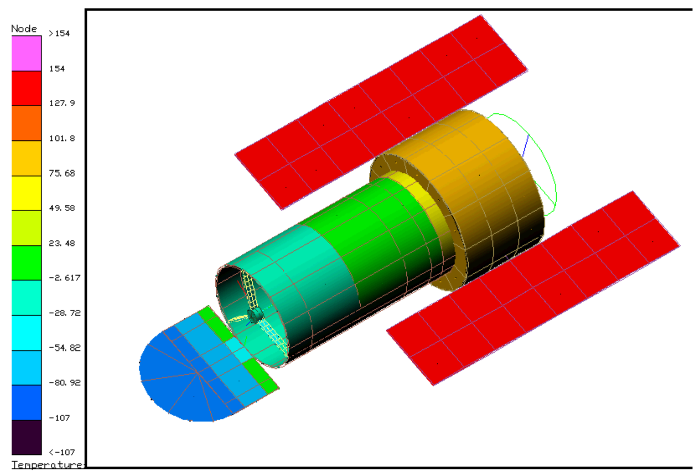

Figure 2: Thermal Desktop Model, External View

Figure 3 depicts an internal view of the rear (hidden) side of the primary mirror. The detailed thermal model of the primary mirror structure is visible, as are the 1D models of the primary mirror flexure struts and the focal plane supports.

The spacecraft was assumed to reside in low earth orbit. Although the model is capable of transient analyses at various beta angles, to keep the execution fast only a single steady-state orbit point was evaluated using an orientation that was expected to maximize temperature gradients on the shell.

Optical Model--Figure 4 displays the surface data for the simple three piece optical model of the telescope. Obscuration by the thin spider supporting the secondary mirror was neglected. This model was used to import Zernike coefficients and calculate the RMS wavefront error for each of the surfaces.

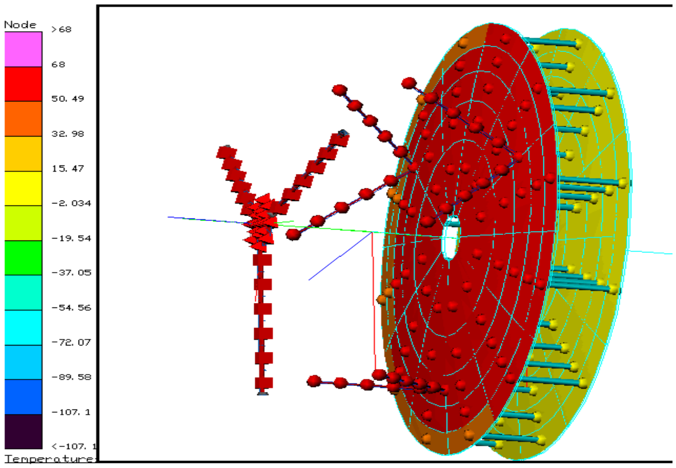

Figure 3: Thermal Desktop Model, Internal View of Detector and Primary Mirror

DESIGN TASK DESCRIPTION

Although many secondary goals exist, the primary goal of OptiOpt is to synthesize thermal/structural designs that minimize mass while meeting required optical performance, without using derived requirements as the basis for generation of the thermal and structural designs. Nonetheless, initial thermal and structural designs must exist, and they must be parametrically modifiable.

Objectives, Design Variables, and Constraints, and Design Evaluation Procedure--The objective for the demonstration task was to produce a viable design which minimized mass. In order to contain the size of the problem, four structural (dimensional) design variables were chosen out of the many possibilities available:

- main shell thickness (range of 0.02” to 0.08” allowed)
- spider thickness (range of 0.2” to 0.7” allowed)
- primary mirror facesheet thicknesses (range of 0.1” to 0.5” allowed)
- flex strut diameters (range of 0.05” to 0.4” allowed)

Since the mass of these components were the only ones that varied, the sum of the masses of these components were used to generate the first part of the objective function (that is, the quantity to be minimized). Recognizing that there must be a penalty imposed upon any heater power used to achieve the required thermal control, it was decided to apply a penalty of 350 lb_m/kW_e to any heat power required. This factor is typical of those used in trade studies to assess the mass costs of thermal control in terms of extra solar panels, batteries, and power management equipment. Use of this factor allowed a single composite objective to be minimized: structural mass plus the mass equivalent of the thermal control system.

Only two thermal design variables were needed to define this design: a base shell heater power and a shell isothermality (gradient) requirement. (Keeping the number of thermal design variables minimized was a challenge: see Lessons Learned below.)

A separate heater element was originally envisioned for the focal plane detector, which was assumed to require control to within the range 68+/-2°F.* However, because the temperature of this component was overwhelmingly influenced by the spacecraft body, which was arbitrarily defined for this example case, it was decided instead to remove this aspect from the demonstration problem by simply holding the detector temperature constant as a boundary condition, and eliminating any detector heater power requirements from the objective function. Obviously, in a real design case with a realistic spacecraft bus, this variation would have been included.

Launch stress constraints were placed on the spider, shell, and struts. However, these limits turned out to be easily met. In the interest of reducing run times, buckling analyses of these components were neglected, but those considerations ended up invalidating many of the lower limits originally assumed. A more important constraint was on the fundamental frequency: 60Hz, which affected primarily the spider design.

* This requirement for the CCD temperature is assumed to result from nonoptical requirements: for stability between calibration and acquisition for improved accuracy.

Lens Data Manager

Surface #	Surface Name	Surface Type	Y Radius	X Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture	Non-Center Data
Object		Sphere	Infinity	Infinity	Infinity		Refract	7330384384.00	
1		Sphere	Infinity	Infinity	0.00		Refract	13.78	
Stop	pm	Conic	-101.43	-101.43	0.00		Reflect	13.78	Global Coordina
3	sm	Conic	-12.38	-12.38	0.00		Reflect	1.56	Global Coordina
4		Sphere	Infinity	Infinity	0.00		Refract	0.65	Global Coordina
5		Sphere	Infinity	Infinity	0.00		Refract	0.40	Global Coordina
Image		Sphere	Infinity	Infinity	0.00		Refract	0.40	
End Of Data									

Figure 4: CODE V Surface Data

Finally, the optical performance was applied as a constraint: a threshold of minimum acceptable performance. A total image wavefront error (WFE) of $0.070\lambda_v$ RMS was applied. Using $0.053\lambda_v$ RMS as the allowance for fabrication and assembly, the CODE V predicted WFE (encompassing design and operation) was therefore $0.046\lambda_v = (0.070\lambda_v^2 - 0.053\lambda_v^2)^{0.5}$. The root mean square (RMS) of the CODE V predicted WFEs resulting from all three optical components was then compared with the allowable limit of $0.046\lambda_v$.

Table 1 summarizes the optimization parameters for the test case. Four of the six design variables are structural (dimensional), while the other two define the thermal control system.

TABLE 1. Test Case Problem Definition

Objectives List	**Design Variables List**	**Constraints List**
mass (minimize)[a]	main shell thickness	Wavefront error < $0.046\lambda_v$ rms
	spider thickness	fundamental freq. < 60Hz
	primary mirror facesheet thicknesses	launch stress constraints
	flex strut diameters	66°F < $T_{detector}$ < 70°F
	base shell heater power	
	shell isothermality (ΔT)	

a.Structural mass plus a power system penalty factor of 350 lb_m/kW_e for thermal heater power

The data flow diagram for the test case is presented in Figure 5. This roughly corresponds to the iSIGHT-generated diagram in Figure 6. However, iSIGHT was unaware of many of the behind-the-scenes data manipulations such as Thermal Desktop mappings of temperatures to NASTRAN

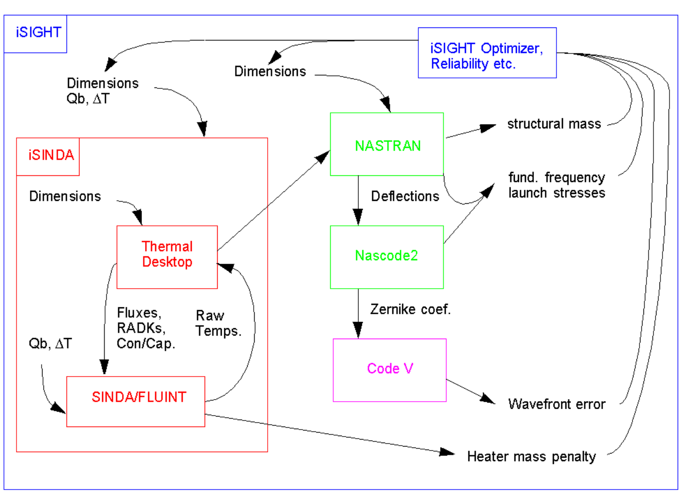

Figure 5: Top-Level Data Flow Diagram

and Nascode2 generation of Zernike coefficients for CODE V.

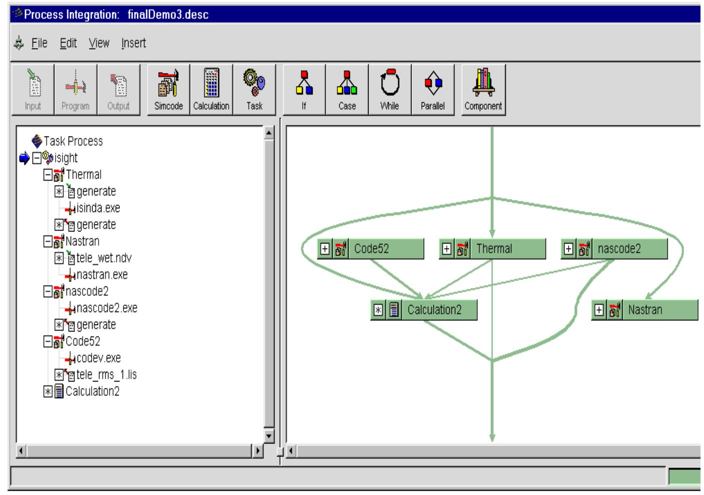

Figure 6: iSIGHT Process Integration Block
(some interconnections were hidden from iSIGHT)

RESULTS OF THE DEMONSTRATION PROBLEM

The demonstration problem was completed successfully in late March of 2001. Results are described in this section.

Approximately 70 to 80 design iterations were required to yield the final design for each case investigated, requiring 2 to 3 hours of total computational time. The computer used was a 450MHz Pentium® II, which is at least a factor of 10 slower than new computers that are now available. Nonetheless, the demonstration case succeeded in proving the operation of the OptiOpt system.

INVAR/ULE DESIGN

The baseline design used an Invar shell and spider along with optical surfaces made with ULE ceramic material. The optimum resulting design was as follows (Table 2):

TABLE 2. Invar/ULE Design, Final Results

Parameter	**Final Value**	**Comment**
PM facesheet thickness	0.1 in	lower limit
PM strut diameter	0.05 in	lower limit
Spider thickness	0.453 in	limited by fund freq.
Shell thickness	0.02 in	lower limit
Base shell heater power	0 W	lower limit
Gradient required	>60 °F	essentially infinite
Total mass	155 lb	all structural, no thermal
Fundamental frequency	60 Hz	constraining
Total RMS WFE	0.0404	*not* constraining

Structurally, all but the spider plate thicknesses were reduced to their lowest possible limits, for a total of 155 pounds for these components. A review of this design, however, revealed that it was susceptible to buckling, which had been neglected. To avoid the extra NASTRAN run times associated with buckling analyses, the lower limits could be raised based on preliminary runs, and the OptiOpt optimization repeated.

The spider thickness was governed by the fundamental frequency constraint.

The resulting values of zero base heater power and larger-than-experienced gradient control requirements (ΔT allowed to be greater than 60°F) are equivalent to *no* thermal control required. The shell temperatures were allowed to drop within the range of 0°F to -20°F with no adverse effect on the optical performance.

However, the most significant result of the resulting design was that the optical performance was better than required: it did not become an active constraint. This means *better-than-required optical performance was achieved with minimum structural components and no thermal control at all.*

With the exception of the buckling limit omission, this design was feasible and optimal. In fact, the ability of OptiOpt to show that very little if any thermal control is required (other than insulation) could be viewed as a significant result. However, to further test OptiOpt with nontrivial thermal control, it was decided to attempt an alternate design using less exotic materials, as described next.

ALUMINUM/SILICA DESIGN

An alternate design was investigated in which aluminum 6061-T6 was substituted for Invar and fused silica was substituted for the ULE ceramic. These alternate materials are considerably less expensive than the initial materials, being multi-source rather than single-source. They are also lighter.

However, they have greater coefficients of thermal expansion (CTEs) and hence represent a challenge for thermal control. It was decided to attempt these materials to see if a design could be found* that used very different materials from those commonly applied in practice.

The final results of this design are listed in Table 3.

TABLE 3. Aluminum/Silica Design, Final Results

Parameter	Final Value	Comment
PM facesheet thickness	0.1 in	lower limit
PM strut diameter	0.05 in	lower limit
Spider thickness	0.451 in	
Shell thickness	0.02 in	lower limit
Base shell heater power	152 W	
Gradient required	2 °F	lower limit
Total mass	189 lb	66 lb structural, 123 lb thermal
Fundamental frequency	75 Hz	*not* constraining
Total RMS WFE	0.046	constraining

* To better enable comparisons with the original design case, buckling was again neglected.

As expected, the structural mass was greatly reduced: from 155 lb to 66 lb. However, a large amount of heater power was required. This heater power, applying the 350 lb_m/kW_e penalty, was equivalent to 123 lb of power generating and management equipment, for a total effective mass greater than that of the Invar/ULE design: 189 lb vs. 155 lb. In a different mission with less penalty for heater power, or one with a bonus for reduced cost, this design might prove superior to the Invar/ULE design.

In this design, meeting the fundamental frequency constraint was not as difficult as was meeting the optical performance constraint. In other words, the previous optimization of the Invar design was mostly a structural optimization, with optical and thermal considerations being negligible. In the aluminum design, both thermal and optical considerations played major roles, thus better illustrating the applicability of OptiOpt to cryogenic designs.

Indeed, the thermal design required to meet the optical requirements would be challenging to realize. The heaters raise the average shell temperature to 60°F, and the resulting gradient requirement of 2°F would be very difficult to achieve in reality. In fact, it likely that a heater solution would be abandoned in favor of a heat pipe solution, adding structural mass in exchange for reducing the heater power by approximately 200W (which is equivalent to 70 lb worth of mass budget for heat pipes).

The higher CTEs of this design would likely require that many more thermal cases be investigated, and that thermal control requirements would ultimately exceed the capabilities of thermostatic or proportional control (e.g., on-board computer control). On the other hand, depending on joint conductances, the lightness of the design can reduce thermal lags and hence might reduce the importance of transient analyses, which can considerably slow the evaluation of each design. (Typically, three to five orbits must be transiently analyzed before a cyclically repeated state can be found, and structural/optical evaluations might be required at many orbit points after that cycle is found.) Finally, the higher CTE's would likely increase the importance of adding optical design variables such as radii-of-curvature and mirror spacings to create additional degrees of freedom necessary to deal with thermal environments, and these in turn could lead to structural changes such as tube length.

In any case, this alternate design provided a good exercise for OptiOpt, and yielded an interesting comparison with the baseline design.

LESSONS LEARNED

While none of the team members of this project are novices with respect to optimization, there was less experience with multidisciplinary optimization, that being a relatively new field. Therefore, a few surprises emerged that will be reported in this section.

THE FOOD CHAIN

It was well understood at the beginning of this effort that a hierarchy existed amongst the three engineering disciplines, as depicted in Figure 7.

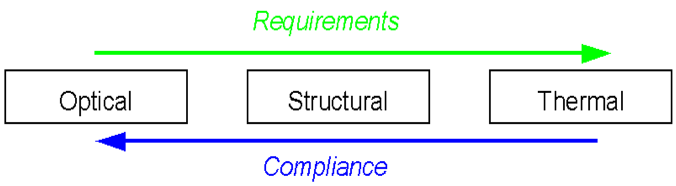

Figure 7: Hierarchy of Disciplines for Thermo-opto-mechanical Design

Optical performance was at the top of the "food chain," being of paramount importance. Structural performance could ultimately be measured only indirectly: in terms of providing adequate stiffness to the optical components; the structural design played a secondary, supporting role. Similarly, the thermal design (including use of low CTE materials) played a tertiary role: minimizing thermoelastic distortions with which the structural design must contend.

Despite the development team's awareness of this hierarchical relationship, the "lessons learned" all derive from its existence. *Automating design production means that the specialties farthest down the chain of flowed requirements have the widest range of variation in design, and are provided with the least specification of critical design cases: they have nothing definite upon which to base even a preliminary design.*

DESIGNING IN A VACUUM

In the traditional approach, firm requirements are generated and flowed down to other disciplines. These requirements are then used to generate a compliant design. The whole idea of OptiOpt is to eliminate the ultimate flow-down of requirements and any accumulated margins and over-design, paying attention primarily to the optical performance.

Unfortunately, this left the thermal designer with no information upon which to base even a preliminary design, and automated optimization really just fine-tunes an existing design rather than generates one from scratch. A novel approach was employed, using OptiOpt not so much to pick a thermal design, but to generate requirements upon which such a more definitive design could be based. It is doubtful, however, that other more realistic applications will lend themselves to such clever solutions.

This same problem exists for the structural design, although in the demonstration problem a preliminary design was already available based on similarity to an existing telescope. Still, this presumed solution may not have been the best design. Ideally, multiple fundamentally different designs should have been used as starting points for fine-tuning during optimization.

Therefore, a need still exists for design requirements to flow from optical to structural to thermal disciplines such that at least one preliminary design (but hopefully multiple dissimilar designs) can be generated as a starting point. In other words, a temporary set of requirements is needed as scaffolding, to be removed upon final optimization such that only the original optical requirements remain.

GEOMETRIC EXPLOSION OF DESIGN VARIABLES

A closely related problem to the above is the fact that the farther removed a design is from the optical requirements, the more flexibility should be available in that design. In other words, if the structural design was allowed a "budget" of ten design variables to allow sufficient variation, then the corresponding thermal design might require ten times that number of variables not only to encompass all the structural variations, but especially to avoid constraining the final answer due to preconceived notions of acceptable solutions.

Theoretically, a "presume nothing and evaluate everything" approach would yield the best possible thermal/structural design. Using the demonstration problem as an example, every possible location on the telescope should have the presence or absence of insulation (of variable mass/performance), the presence or absence of a heater (with variable size and control parameters) and perhaps Peltier cooler, etc. The number of possible design variables would be staggering. Worse, every possible design condition must be included in the evaluation in a transient mode, since it cannot be known a priori which time slice of which orbit yields a critical design case for the optical performance metric.

This untenable scenario was avoided in the demonstration problem, restricting the thermal design variables to even less than the number of structural variables (two versus four). Unfortunately, such a solution is not generically applicable to all missions.

One possible general-purpose work-around would be *sub-domain optimization*, once again relying on temporary flowed-down requirements as scaffolding. For example, the engineer might use optimization to find a meaningful thermal design *per structural design*, using temporary requirements on CTEs and gradients. These paired pre-optimized thermal/structural designs would then be reassessed at a higher level (with reduced variations) using the ultimate optical and mass constraints and objectives and dispensing with the temporary thermal/structural requirements.

GEOMETRIC EXPLOSION OF CASES

Yet another problem resulting from the hierarchy of disciplines plagued this type of multidisciplinary work: even after a solution has been found to the absence of design *requirements*, and even after containment of design *variables* has been achieved, an absence of design *cases* remains. In other words, once preliminary structural and thermal designs have been generated and the narrowest possible variations of those designs have been specified, against which environments, loads, scenarios etc. shall these designs be evaluated?

To illustrate this problem, consider again the demonstration problem. A single steady state design case was chosen to keep the demonstration tenable. This case was selected assuming it would cause the worst temperature gradients from one side of the shell to another, and that this would in turn cause the worst thermoelastic distortions, and that these would in turn cause the worst optical performance.

To avoid such assumptions, one must explore all possible orbital positions and orientations, evaluating not only the structural but also the optical responses at each point. *This exhaustive evaluation would in theory have to be repeated for every point design candidate* (including gradient-seeking perturbations) attempted by the optimization engine since the worst case for one design candidate might not be the worst for another. Tens to hundreds of such point designs must be tested per optimization task.

In fact, the situation is far worse: such steady states cannot be presumed to be the bracketing worst cases for design evaluation purposes. Instead, for every beta angle investigated during the evaluation of each and every point design, many transient time slices (perhaps 20 to 30 per orbit) must be evaluated as a potential worst case, requiring a structural and optical solution each time. As was mentioned before, each such orbital transient requires simulation of *at least* three prior orbits to achieve a repeatable cycle, washing out the effects of initial conditions. In other words, a purely "hands off" optimization with no presumptions or limitations is untenable and probably always will be.

To some extent, this problem can be ameliorated using testable assumptions. As an example, in the demonstration problem assumptions were made to avoid the recalculation of thermal radiation effects and optical obscuration effects when the spider thickness changed.

Ironically, optimization technology itself can offer a generalized work-around. Instead of seeking the best design, it can also be used to find the worst case. Continuing the demonstration problem, and assuming steady state solutions were still adequate, OptiOpt could have been used to find the beta angle and vehicle orientation that resulted in the *worst* rms wavefront error (WFE), holding the thermal and structural and optical designs constant. Specifically, WFE becomes the objective to be *maximized*, and the beta angle and orientation angles become the "design variables". (Other variables might include uncertainties in optical properties, solar panel positioning, etc.) This procedure would yield a worst case scenario that could then be used for subsequent minimizations of weight, making the relatively minor assumption that this worst case for the initial design was also the worst case for other designs. This assumption could be easily tested by repeating the worst-case seeking analysis using the final design parameters.

REASONABLE EXPECTATIONS

Even with future advances in software and computer speeds, it is unreasonable to expect multidisciplinary optimization to magically synthesize designs without out reasonable starting points. Nor can MDO be expected to investigate all possible variations under all possible circumstances. Intelligent and clever engineers trained not only in their specialties but also in the basics of optimization are required. Foresight, reasonable and testable assumptions, subdomain investigations, and worst-case explorations are all necessary ingredients.

FUTURE WORK

Significant successes were achieved, but many expansions are improvements are needed before multidisciplinary design environments are deployed extensively. Potential next steps include:

1. *Exploitation of NASTRAN Design Sensitivities.* The inexpensive existence of design sensitivity information produced by NASTRAN could be exploited to reduce the need for top-level iterations. Unlike NASTRAN, however, Thermal Desktop would have have had to be run iteratively to produce the required sensitivity information, so the addition cost of thermal solutions might easily overwhelm the benefit achieved by fewer outer iterations.
2. *Structural/Optical Interactions.* Several structural designs make use of compensating optical sensitivities. One example is a Serrurier Truss where gravity deformations (and/or G-release) cause primary and secondary mirrors to deflect in compensatory ways. Likewise mounts can be configured such that elements rotate about their centers of curvature. OptiOpt could eventually help to configure mounts and structural designs that optimally benefit from optical sensitivity compensations.
3. *Thermal/Optical Interactions.* Examples of designs requiring tighter thermal/optical communication include high power laser cavities and lenses with temperature-dependent indices of refraction (especially in lenses heated either intentionally for focusing purposes or unintentionally as a result of high flux optics such as splitters for lasers). Note that, since the initial completion of OptiOpt, Sigmadyne's SigFit (an expansion of the NASCODE tool created for this project) has been expanded to include tem-

perature-dependent indices of refraction as well as stress birefringence (Ref 4).

4. *Integration with IMOS.* IMOS (Ref 3) is a MATLAB-based program similar in intent to OptiOpt: it seeks multidisciplinary thermo-opto-mechanical design, and is especially suited to conceptual design. Unlike OptiOpt, IMOS does not neglect active control systems including active alignment and adaptive wavefront control systems. Since OptiOpt's emphasis is instead on the fine-tuning of detailed designs, means of translating from IMOS to OptiOpt is especially appropriate. Note that, since the initial completion of OptiOpt, SigFit has been expanded to include adaptive wavefront control (Ref 4), and SINDA/FLUINT has been expanded to include a COM-based MATLAB interface.
5. *Reintegration with Other Multidisciplinary Design Environments.* Other commercial MDO/MDA packages include Phoenix Integration's ModelCenter®, MSC Software's MSC/RD, Synapse' Pointer®, VR&D's VisualDOC®, Sandia's DAKOTA, LMS' Optimus®, and Samtech's BossQuattro.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

API .... Application Programmer Interface
CAD .... Computer Aided Design
CTE .... Coefficient of Thermal Expansion
CODE V .... Optical analyzer from ORA
FEM .... Finite Element Modeling
FP .... Focal Plane
I/O .... Input/Output
iSIGHT .... MDO Environment from Engineous
MDA .... Multidisciplinary Design Analysis
MDO .... Multidisciplinary Design Optimization
NASTRAN .... Structural analyzer from MSC Software
NASCODE .... Structural/optical conversion utility from Sigmadyne
NGST .... Next Generation Space Telescope
OptiOpt .... Name of this project/product
PM .... Primary Mirror
RadCAD .... Radiation analyzer in Thermal Desktop
RMS .... Root Mean Square
SINDA/FLUINT . Thermal/fluid analyzer from C&R Technologies
SINDA .... Thermal side of SINDA/FLUINT
SM .... Secondary Mirror
Thermal Desktop .... CAD-based thermal modeling environment from C&R Technologies
WFE .... Wavefront Error