Integrated approach to opto-mechanical system development

Thomas E. Reney, Richard L. Wiggins, Lovell E. Comstock, Jeffry J. Santman, Kenneth S. Woodard
Corning, Inc. 69 Island Street, Keene, NH 03431

ABSTRACT

Over the past few decades of computer aided engineering growth there has been much more progress in increasing the power and capability of function specific engineering tools (e.g., optical design, finite element analysis, etc.) than in the integration of and communication between these tools. With only a few notable exceptions, such as FEA being imbedded into solid modeling, the communication method between the function specific tools continues to be dominated by translation to neutral data formats (e.g., IGES, STEP) and file transfer. There are a number of problems with this approach. The translation is a serial process where an engineer has to stop at some point in the design, make the neutral file, send that file to the next function, and wait for feedback. The translation through a neutral format is typically one way so the whole translation process has to be repeated when changes are required. Revision tracking of multiple files for each design iteration is both critical and a likely source of errors. Also, as with any translation, some information is always lost or corrupted in the process.

This paper describes some progress that has been made in more tightly integrating optical design, mechanical design, fabrication, and testing of optical systems. Tools have been developed that connect CODE V®[1] to SolidWorks®[2] (bidirectional), compensation of diamond turning CNC from interferometric data, slope analysis from interferometer and profilometer data, and other tools for wavefront error compensation, and electronic nulls. Design, machining, testing and inspection efficiency gains are achieved through tools that consume mechanical solid models in their native format.

Keywords: Opto-mechanical, null, wave front error

1. INTRODUCTION

The development of opto-mechanical systems requires efficient and effective communication between the various engineering functions. Of particular interest is the transfer between the optical and mechanical designers. The requirement for smaller and lighter systems results in an iterative design process where a solid connection between design tools is required to minimize iterative cycle time and to minimize errors in the transfer of design data. The need for solid data communication also includes the transfer of the design data to fabrication and test. Throughout the manufacturing process there are opportunities for the direct use of engineering information, to improve communication of requirements or that the requirements have been met, and to use test data to facilitate component production. These opportunities extend to component and assembly test where measurement data and design information can be used to aid in component selection, system alignment, and system and component verification.

2. CODE V® TO SOLIDWORKS®

A typical method for bringing an optical model into a mechanical model is to export the model from the optical design software in a neutral format and then import that file into the mechanical design software. The end result of the exporting to and then importing of neutral format files is often errors that are not always easily fixed. The imported part models are nominally editable: features can be added but existing features cannot be edited. Limited information can be gleaned from these imported models. For instance, no information about the optical surface shape, vertex location, or tilt can be mined from an imported off-axis primary mirror model. Some mechanical computer-aided design, MCAD, software packages include a feature recognition function, but these do not recognize complex geometric features such as those mentioned for an off-axis aspheric surface. If the optical model changes then a new neutral file must be created and imported. This process can result in many errors and considerable rework of the mechanical model.

Another method is to provide the mechanical engineer with the optical system details: surface prescriptions, air spacing, off-axis dimensions, etc. from which the mechanical design engineer generates all the components and the optical

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assembly. This can be a tedious and time consuming process and there is high likelihood of errors due to the manual entering of parameters.

To improve the communication between optical and mechanical design we developed software that accesses a CODE V® .len file and extracts the required model information such as surface prescriptions, air spacing, footprint data, etc. See figure 1. The program next attaches to SolidWorks® and generates part and assembly files, traces the footprint on each element, and lofts between the footprints to create an optical path envelope. See Figure 2.

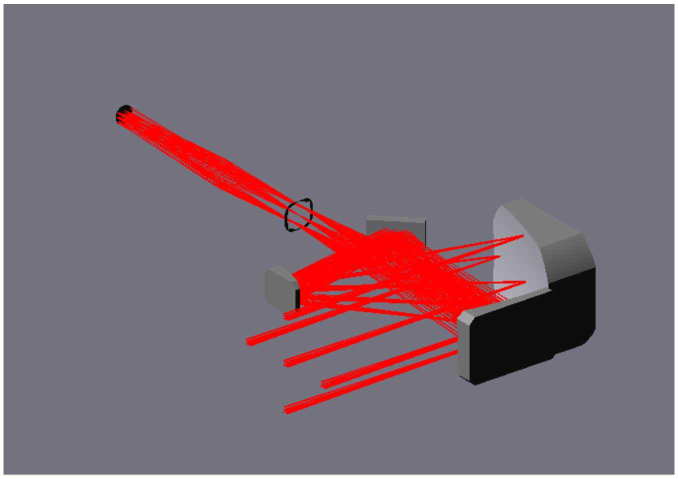

Figure 1. Optical design as created in the optical design software.

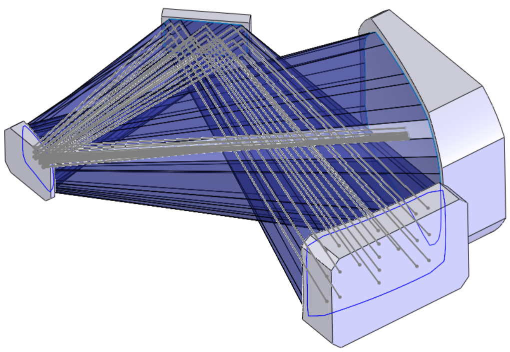

Figure 2. Optical design as recreated in mechanical design software.

The mechanical models are fully editable since they were created in the mechanical design software. The opto-mechanical designers can add features such as mounting tabs, flanges, light-weighting cuts, holes, etc. to complete the part model. If a change is required to the optical model the software is run again to update the mechanical model. The software edits the SolidWorks® files to update them so features previously added by the mechanical designer are preserved.

3. COMPENSATION OF DIAMOND TURNING CNC FROM INTERFEROMETRIC DATA

20 years ago diamond machining was typically applied to the manufacture of optical components for long wave infrared (LWIR) applications. More recently, however, multi-spectral optical systems performing in bands extending down through the visible spectrum require optics with lower surface figure errors. Although the latest generation of diamond machining equipment has significantly improved performance through better thermal stability, stiffness, feedback resolution, and control system advances a number of factors still produce figure errors.

These figure error producing factors include:

- Diamond tool errors including radius and irregularity; tool wear; centrifugal force deformation – particularly on light-weighted, off-axis components;
- Vacuum fixuring;
- Toroidal errors associated with the location of the tool path relative to the spindle axis;
- Orthogonality of the machine tool axis
- Misalignment of the spindle axis to the machine tool axis.

All of these errors are repeatable and can be compensated for by utilizing interferometric figure data to create a compensated computer numerically control, CNC, program. The correction of radius errors requires particular attention to the interferometric test to assure the component is tested on the correct conjugates.

Applying the profile error to the CNC program also presents a number of challenges. The data can have noise related to pixilation, can have edge effects due to focus, and the error must be precisely aligned to the CNC program. Mathematical techniques can be applied so that noise does not contribute to surface finish that has its own set of constringent requirements.

This technique is not limited to the manufacture of components, but can be applied to optical systems to correct for not only the figure errors of the components, but also their alignment errors within the system. Particular care must be taken in selecting the component to compensate due to issues related to extended fields of view. Figures 3 and 4 below are examples of an off-axis reflective asphere before and after compensation. [3]

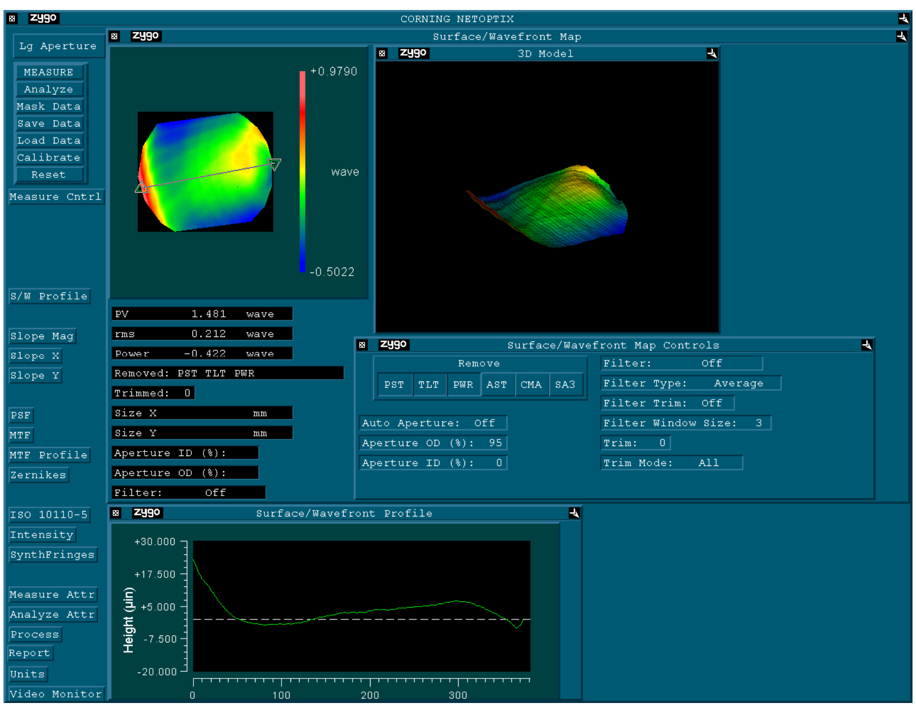

Figure 3. Data and interferogram of an off-axis reflective asphere before compensation.

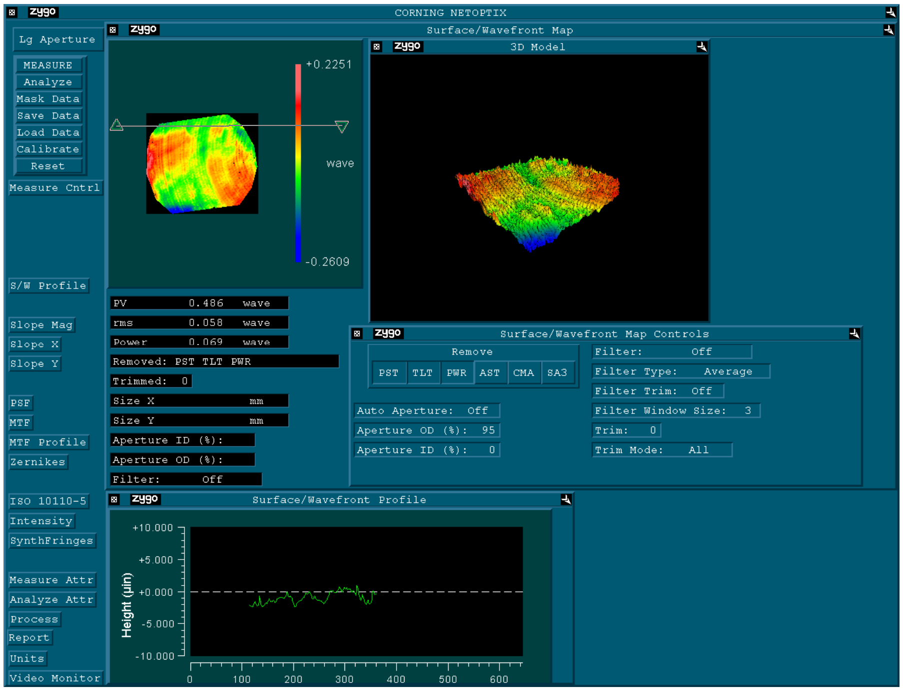

Figure 4. Data and interferogram of an off-axis reflective asphere after compensation.

4. SLOPE ANALYSIS FROM INTERFEROMETRIC AND PROFILOMETER DATA

Surface figure measurements are typically performed using a Fizeau interferometer or a contact profilometer. While the interferometer software does report slope error it is not a simple process and does not provide a pass or fail result. Profilometer software does not analyze slope. Since slope error is a commonly specified requirement for optical components[4] InterSlope and TalySlope were created.

InterSlope imports xyz data representing the phase difference between actual and reference wavefronts at each pixel. InterSlope requires the user to enter the slope specification as microinches per inch over a length in inches. The XYZ map is reimaged to a resolution equal to half the specification length. The Z value of the new pixels is the average of the Z values of the original pixels it contains. A gradient magnitude calculation is performed at each pixel to determine the slope. The software reports the maximum slope and colors reimaged pixels red if they violate the slope specification.

TalySlope imports XZ data from the profilometer and determines the slope of a best fit line through the points over the specification range. The difference between resulting slope and the slope over the same points for the design curve must be less than or equal to the design specification. This test is performed for all points along the curve. The software reports the greatest slope and the Pass or Fail result.

5. TESTING WITH AN ELECTRONIC NULL

The "retrace errors" associated with interferometric testing are well understood[5][6][7]. These errors occur when the reference and test beams have unequal path lengths within the interferometer. To a large extent these errors can be deconvoluted after measurement of the instrumental function of the interferometer.

Lowman and Greivenkamp[5] and Szwaykowski and Raymond Castonguay[7] have estimated the error without retrace correction. Both papers show that when the number of fringes is less than 25 the peak-to-valley retrace error is less than $\lambda/5$. In our experience the aspheric terms in many optics produce less than 25 fringes when tested against a conic and the PV retrace error is acceptably small. We have developed a procedure for testing in this region, which we refer to as testing with an electronic null. The procedure is conceptually simple.

We use ray tracing to determine the expected wavefront error of a perfect test surface in the test configuration. Most software will create such wavefront maps at resolutions, typically 512 x 512, that are comparable to the resolutions of the cameras used in interferometers. We output this synthetic wavefront as our electronic null.

We input the electronic null into the interferometer acquisition software. 4-Sight by 4D[8] in particular offers simple tools for such import. The electronic null is used as a reference that is subtracted from each wavefront measurement. If the test part is perfect, the acquired and reference wavefronts are identical and the result of the subtraction is flat.

In practice, a successful subtraction requires that the image of the test part must match the size and orientation of the synthetic test part in the electronic null. The allowed mismatch can be approximated as

mismatch [mm] = acceptable_test_error [fringes] / wavefront_slope [fringes /mm]

Use of fiducials and attention to detail can keep the mismatch to two pixels. If the image size is approximately 250 pixels, and the fringe count is less than 25 then the error will be less than 0.2 fringes.

6. INTERFEROMETRIC TOOLS FOR SIMPLIFYING THE ALIGNMENT AND TEST OF COMPLEX OPTICAL SYSTEMS.

6.1 Level 1 – electronic nulls, and the use of RDWFE map subtraction to drive non-zero optimization.

Optical modeling software can be used to produce 3D wave-front error, WFE, maps depicting the residual design wave front error, RDWFE, of a given optical component or system. These WFE maps can be imported into the analysis software of most commercially available phase-shifting interferometers as WFE data maps and used by the software as a subtracted reference for analysis of actual measurements.

This method of non-zero optimization for component testing makes it possible to measure the accuracy of certain aspheric surfaces without the expense and complexity of computer generated holograms or customized non-spherical return nulls. The modeled WFE of the component is combined with the actual measured WFE of the part under test and the deviation from nominal accurately determined.

This method of non-zero optimization for system testing makes it possible to drive the performance of an optical system to match a particular desired WFE. This is particularly useful for verifying the performance of an optical subassembly that is designed to correct or compensate for a particular WFE generated by a device upstream in the overall optical path of a complex optical system. This is especially useful if the upstream device is not available for the test.

This was the case in the recent construction of several telescopic subsystems manufactured by Corning, Inc. for the James Webb Space Telescope's Fine Guidance Sensor[9]. In practice, the subsystems being tested would be fed by the JWST's main telescope, or Optical Telescope Equipment, OTE, which has a well known and well characterized RDWFE for the fields of view which the subsystems were using. The OTE was obviously not available for the testing of the subsystems it fed. The RDWFE maps of the OTE for the specific fields of view were generated in optical modeling software, converted into WFE map data native to the interferometer used for the subsystem testing, and then used as subtraction references that altered the WFE of the interferometer's apparent interrogation beam to match the output of the OTE. In this way, the sub-system's performance in correcting the OTEs inherent RDWFE was validated.

6.2 Level 2 – Using actual WFE data from "upstream" components and/or subassemblies along with UUT modeled performance, to assist in system alignment.

A variation on the technique described above in Level 1 is to use the actual output WFE maps from an upstream subsystem, as opposed to the modeled RDE map, along with the modeled RDWFE map of the unit under test to assist in determining compensatory movements of the unit under test, UUT, components. This is useful when the upstream devices themselves are unavailable or impractical to incorporate into the testing of the downstream subsystem.

Again, using the recent JWST/FGS program as an example, two telescopes being used in series downstream of the OTE were to be tested to verify that:

1. The first device was accurately correcting for the OTE RDWFE as well as characterizing its WFE output specific to the application.
2. The second device was correcting for any manufacturing tolerances in the first device, and producing the desired output for the overall optical system.

In this particular case it was impractical to assemble the two devices for testing in series due to other mating equipment being unavailable and the OTE being unavailable to provide an actual distorted interrogation beam. The testing of the first device was performed as described in Level 1, above. The output of this device was then stored as WFE maps and after careful consideration of orientation, etc. imported into the optical model as entrance pupil maps for each of the fields of view the devices were to be tested at.

Using the optimization routines of the optical modeling software, individual optical components were virtually adjusted in position to produce the desired compensating WFE performance of the second device. This information was then used to guide the adjustment of the actual mirrors in the UUT and the final performance was verified.

6.3 Level 3 - Incorporating as-built component surface figure error maps into assembly models for component selection and alignment optimization

As mentioned in Level 2 above, it is possible and practical to import actual surface figure error maps, SFE, from interferometric measurements of optical components into optical modeling software to alter the performance of a modeled optical system. Using this technique it is possible to determine the best combination of components from a given selection. It is also possible to determine the likely compensatory movements of those components during actual assembly and alignment of an optical system. This technique is a very useful timesaver, particularly in short-run production situations when building a small number of devices from a limited number of components. The ability to mix and match components and then optimize alignment using virtual hardware as opposed to real hardware minimizes the handling of hardware and streamlines assembly and alignment processes dramatically.

It should be noted that importing computer generated SFE maps into interferometer software and importing interferometrically generated SFE maps into optical modeling software is simple to define, in practice it requires significant forethought and verification to insure that the maps are properly scaled, aligned, and oriented for their intended use. This is of particular importance when multiple fields of view and multiple devices are involved. Mirror imaging of WFE maps, phase-inversion of the WFE, and misalignment of relative fields of view between devices are frequent causes of analysis errors. While using these computer aided techniques is significantly faster than testing with the actual hardware they are not simple to prepare and an appropriate amount of schedule should be set aside for determining and then verifying the details.

7. DESIGN, MACHINING, TESTING AND INSPECTION EFFICIENCY GAINS

In addition to the specialty tools described above there are other tools available to facilitate effective and efficient communication amongst the various engineering and manufacturing functions.

Development of an opto-mechanical system is an iterative process: designs change. Mechanical analysis is performed not just to predict how well a design will stand up to the specification conditions but to provide feedback from which to optimize the design for those conditions. The mechanical designer and the analyst are expected to go back and forth so it is important to have design and analysis tools that work well together. Therefore it is desirable use mechanical analysis software that will open the mechanical design models in their native format. Better still is the ability to save optimized files so the designer can use them directly. A set of guidelines for design and analysis can further improve this process. For instance, designers should consider the analysts need to simplify models as they create the design. Analysts must mesh the parts so the ability to quickly suppress fillets and similar features to simplify the model greatly speeds the process.

The use of engineering solid models in manufacturing offers cost savings though reduced machine programming time and improved quality by reducing programming errors. The cost savings begins in engineering. Drawing can be created with only critical dimensions and notes since manufacturing will create machining and inspection programs to the models. In some cases drawings can be eliminated completely. Guidelines must be created for this to work properly. For instance, the machine programmer needs to know the model condition relative to specified tolerances: is the model feature at the mean of the tolerance, the maximum, or the minimum. We find that using the mean of the tolerance simplifies notes that specify the tolerance for non-dimensioned features.

In our machine shop we use computer aided manufacturing, CAM, software packages that consume our mechanical models in their native format. Both packages validate the program against the current released model and tell the programmer if all is correct or if the program must be edited. In mechanical inspection we use software for the coordinate measuring machines, CMMs, that uses our mechanical models in their native format and, like the CAM software, verifies that the current model matches the model used when the program was created.

8. CONCLUSION

The development of Opto-mechanical systems requires strong communication between the various engineering and manufacturing functions. Tight integration of these functions through the application of specialty and commercially available software tools is critical. Connectivity tools allow engineers and designers to spend more time developing systems and implementing design iterations rather than recovering from them. These close ties between optical design, mechanical design, and analysis are essential to rapid and effective development. Much can be gained through the proper selection of commercially available tools, the creation of guideline, and the development of custom tools.

More benefits are gained by extending this integration into manufacturing and testing. Operators can compensate for many symmetric and repeatable error sources. Operators receive clear results of slope analysis, pass or fail, without having to interpret test data. Interferometer test results can be used in optical design software and optical design data can be used in interferometer software in many ways to improve the testing of components and systems.

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