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Interactive CAD Layout of Reflection-Based Mirror Metrology Systems

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Abstract. Concentrating solar mirrors need to accurately focus sunlight onto a receiver. Since mirror surface normal determines reflected light direction, reflection-based metrology methods that measure surface normal have the advantage of directly measuring the mirror's intended functional performance characteristic. Several methods have been reported that produce high-resolution measurements of mirror surface normal of concentrating solar mirrors [1-8]; these systems typically employ an optical target, a camera, and sometimes an external light source. These elements must be placed in a configuration that satisfies multiple feasibility constraints, including mechanical and optical visibility and reflection constraints. For complex problems or installations in cluttered environments, it can be difficult to analyze all of these constraints manually. We have created a computer automated design (CAD) tool that aids in visualization of reflection-based metrology systems, making it possible to determine layouts for complex metrology design problems. The tool is implemented SolidWorks, a commercial CAD system [9]. By exploiting the SoidWorks constraint satisfaction mechanism, the tool is able to present interactive visualization of reflection and field of view constraints in real time without any additional code or macros. The tool supports ease of use and multiple design configurations through an ordinary spreadsheet interface. The tool can be used to address a variety of reflection-based metrology design problems, and is available to the public as open source.

Keywords: Deflectometry Design, Metrology Design, CAD, SolidWorks, SOFAST, Reflection

1. Introduction

Concentrating solar mirrors are designed to focus sunlight onto a receiver, and must do so accurately to achieve high solar concentration. For each point on a mirror, the mirror surface normal determines the direction of the reflected light. Consequently, reflection-based metrology methods that measure mirror surface normal have the advantage of directly measuring the mirror's intended functional performance characteristic. Measurement methods that measure mirror surface normal for a dense sampling of points across the mirror surface can detect both large scale macro and high-frequency detailed reflection effects. Several systems have been reported that produce high-resolution maps of mirror surface normal for concentrating solar mirrors [1-8]; these systems typically employ an optical target, a camera, and sometimes an external light source. These elements must be placed in a configuration that satisfies multiple feasibility constraints, including both mechanical clearance and optical constraints, such as ensuring that the optical target reflection fills the mirror, the mirror is completely contained within the camera's field of view, the projector's field of projection spans the optical target (if included), and line-of-sight occlusions are avoided. For complex problems it can be difficult to analyze all of these constraints simultaneously. We report a computer automated design (CAD) tool that aids in visualization of reflection-based metrology systems, making it possible to determine layouts for complex metrology design problems.

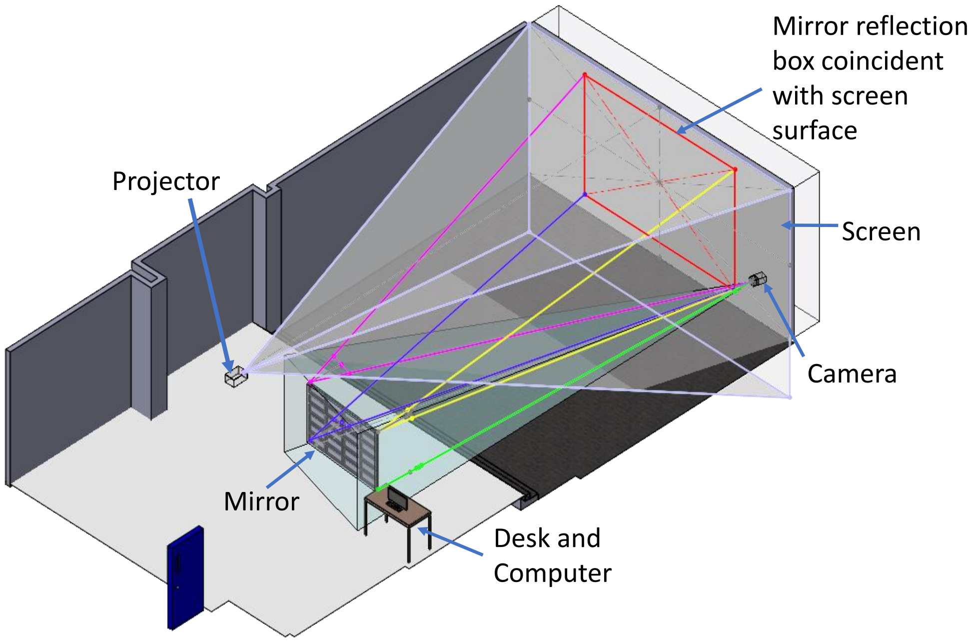


Figure 1. *SOFAST configuration in the Sandia NSTTF Optics Laboratory.*

We originally created the CAD tool for internal purposes, such as analyzing whether a given mirror could be measured by the original SOFAST setup in the Sandia National Solar Thermal Test Facility (NSTTF) Optics Laboratory (Figure 1). We have since used the tool to design advanced SOFAST setups, such as the examples shown in Figure 8, along with other more complex examples.

Designing a new reflection-based metrology setup can be difficult to visualize, given the constraints of a given installation site and required functional capabilities. To help facilitate design, we created an interactive CAD design tool, based on the SolidWorks CAD system [9]. This tool aids in visualization, and updates the mirror reflection using Snell's Law, projector field of projection (FOP), and camera field of view (FOV) in response to design inputs. It also supports the design of complex systems through the use of configurations and design tables.

2. The Design Problem

Fringe deflectometry is a reflection-based metrology method utilized by several previous systems [1-5, 8]. Figure 1 shows the primary components of a deflectometry system: mirror, camera, optical target (either screen illuminated by a projector, or an active display). A valid deflectometry layout must satisfy four optical requirements:

1. The reflection of the screen seen by the camera (the "mirror reflection") is contained within screen's boundary. This ensures the reflection of the optical target seen by the camera fills the mirror.
2. The mirror is within camera's field of view (FOV).
3. The projector's field of projection (FOP) spans the required screen area. Note the FOP may spill off the edges of screen.
4. The mirror reflection, FOP, and FOV optical paths must not be occluded.

In addition to these requirements, the system hardware must fit within the physical constraints of the space. Finding a design that meets all of these requirements can be difficult, due to coupling between components. We addressed these difficulties by creating an interactive SolidWorks CAD tool, which updates the mirror reflection using Snell's Law, projector FOP, and camera FOV in response to design inputs.

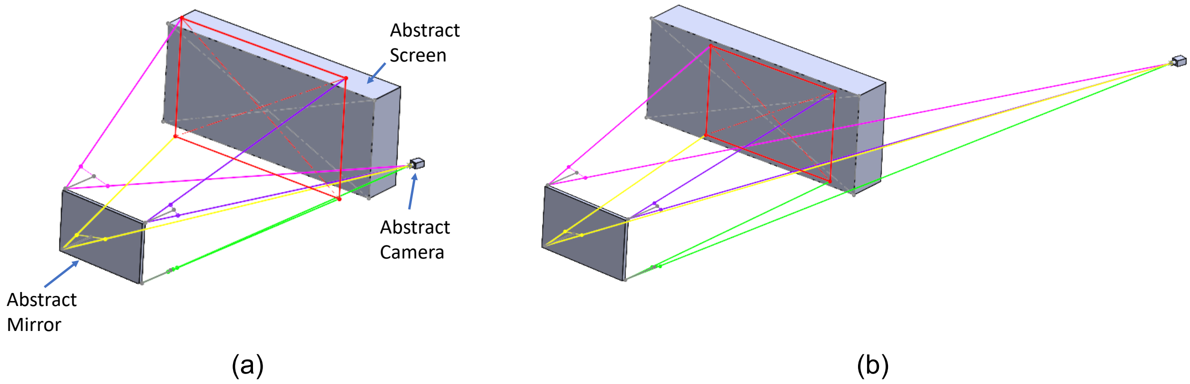


Figure 2. *(a) Mirror reflection too large. (b) Mirror reflection within screen after adjusting camera position.*

Figure 2 shows an example design challenge. Part (a) shows a typical configuration where the camera is slightly in front of the optical target screen. Because of the size of the mirror, the mirror reflection exceeds the boundaries of the screen. One solution to this is to move the camera behind the screen, which reduces the size of the mirror reflection (b). The CAD tool updates the mirror reflection in real time, interactively showing the effect of this and other position adjustments. This makes it easier to explore design adjustments to find a feasible solution and evaluate tradeoffs between alternative solutions.

3. Implementation of CAD Tool

The tool is implemented in SolidWorks [9], a 3-d CAD design system for designing mechanical parts and assemblies. SolidWorks includes a constraint satisfaction system for both part features and assembly mating relations, enabling flexibility in model definition. These and other SolidWorks features enabled us to implement the design tool with no code or macros.

3.1 Representation of Optical Function

A key feature of the metrology CAD tool is an explicit representation of optical functionality. This is accomplished by combining a *concrete model*, to check for mechanical interference, and an *abstract model,* representing optical function. These are shown in Figure 3.

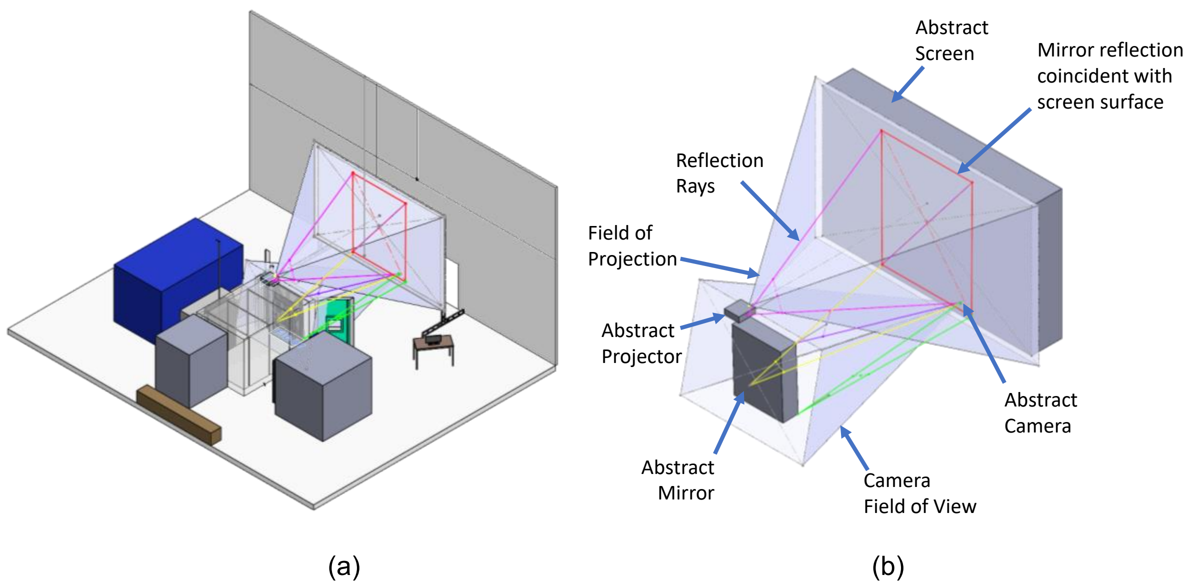
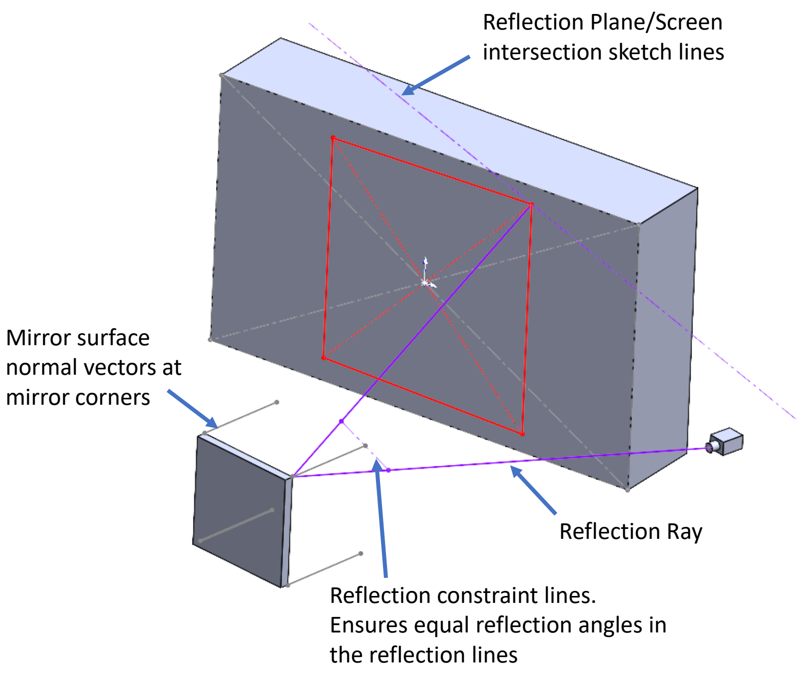
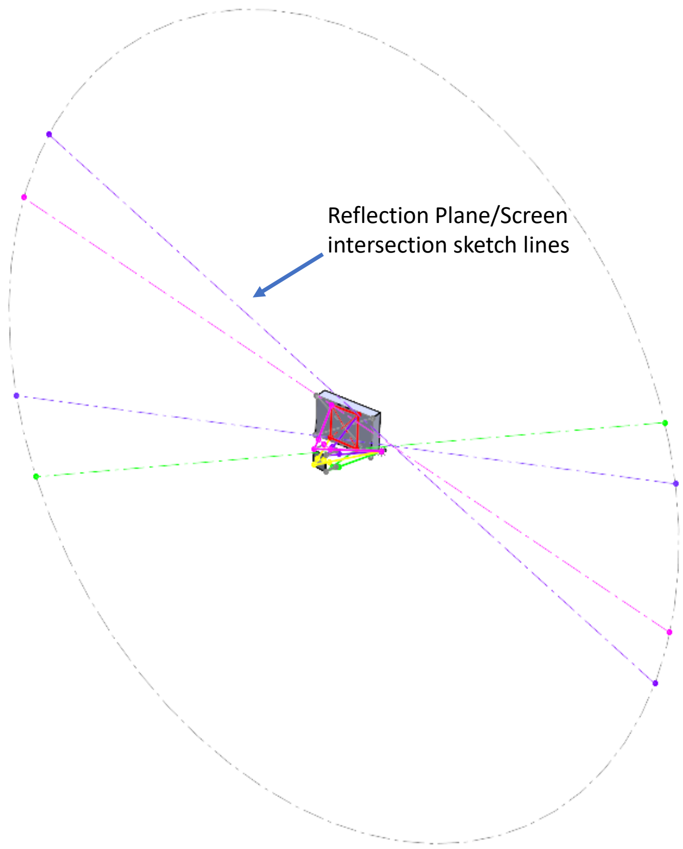


Figure 3. *An example metrology system model. (a) Concrete model showing geometric components in the environment. (b) Abstract model representing optical function.*



(a) Reflection Construction



(b) Constant Topology Construction

Figure 4. *(a) Reflection construction. (b) Constant topology construction.*

The role of the abstract model is to illustrate the optical constraints 1-4 given in Section 2 above. Figure 4 illustrates the implementation of the interactive mirror reflection model in SolidWorks. The mirror reflection (red) is automatically updated when the mirror, camera, or screen are moved (e.g., as shown in Figure 2). This is accomplished using the SolidWorks built-in constraint satisfaction system. Sketches define the mirror corner surface normal

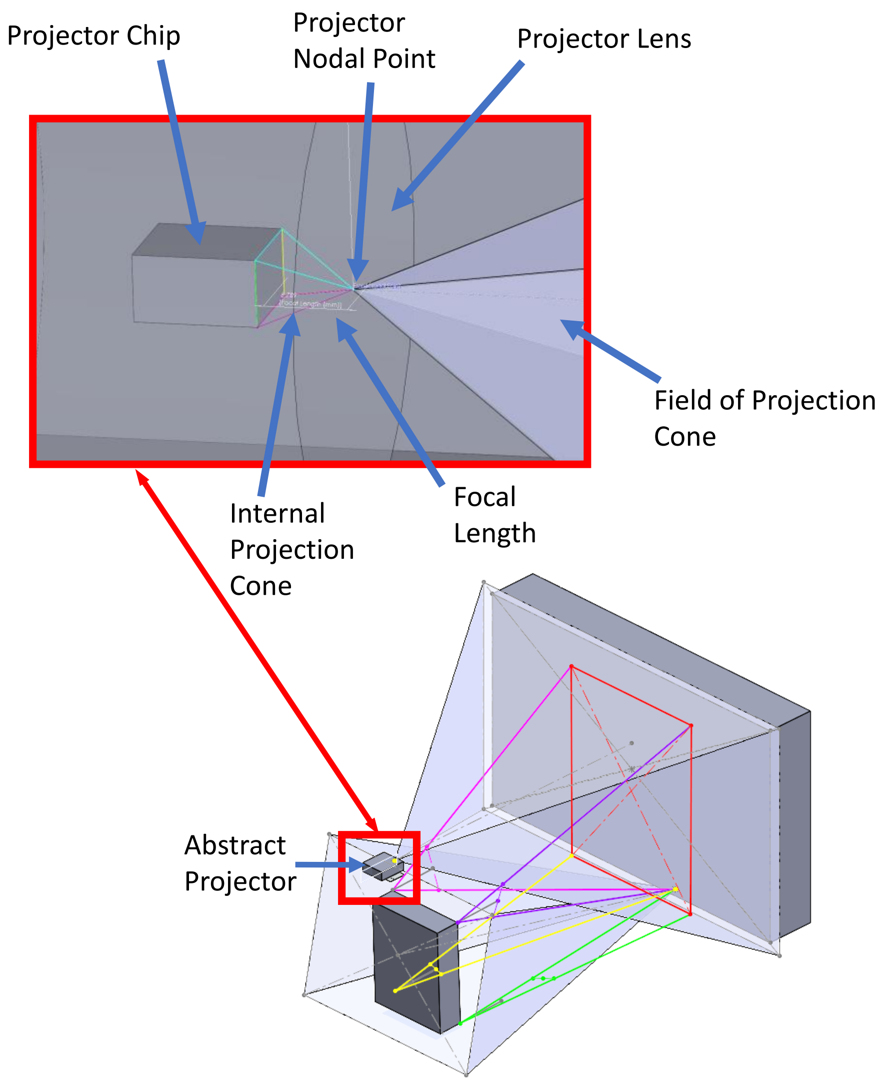
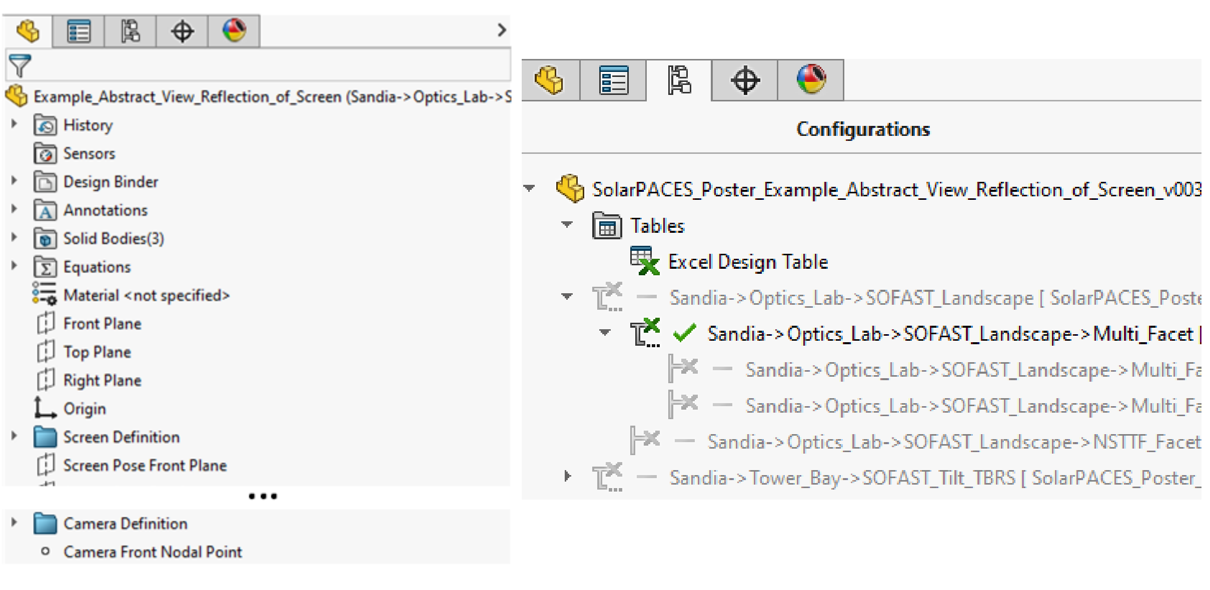


Figure 5. *Field of projection construction.*

vectors, and for each corner, a reflection plane is defined by two line segments (Figure 4(a)). The first segment connects the camera lens front nodal point and the mirror corner, and the second segment is the mirror surface normal at the corner. The resulting reflection plane includes both the incident and reflected light rays: from the camera to the mirror corner, and from the corner to the screen. Cross lines are added with coincidence, equal length, and other constraints to enforce Snell's Law of Reflection. Intersection lines defined by the reflection plane and screen constrain the reflected ray endpoint, and a large circle is used to ensure model robustness and avoid varying topology (Figure 4(b)), as the mirror reflection changes shape and position radically with various design adjustments. These intersection lines can be seen in Figure 4(a) as "Reflection Plane/Screen intersection sketch lines," and the large circle that allows for carrying topology, can be seen in Figure 4(b).

The abstract optical model also includes a representation of the camera's field of view (FOV), and projector's field of projection (FOP). Both are displayed as cones with shape depending on the lens focal length and image chip size. To achieve this, the abstract projector and camera contain a pinhole optical model including the imaging chip and lens nodal point. The defined focal length controls the image chip position relative to the nodal point, which in turn updates the cone angle to the proper FOV or FOP. The projector model also incorporates lens shift in X and Y, simply by moving the lens nodal point laterally. Figure 5 illustrates the abstract projector field of projection model.



(a) (b)

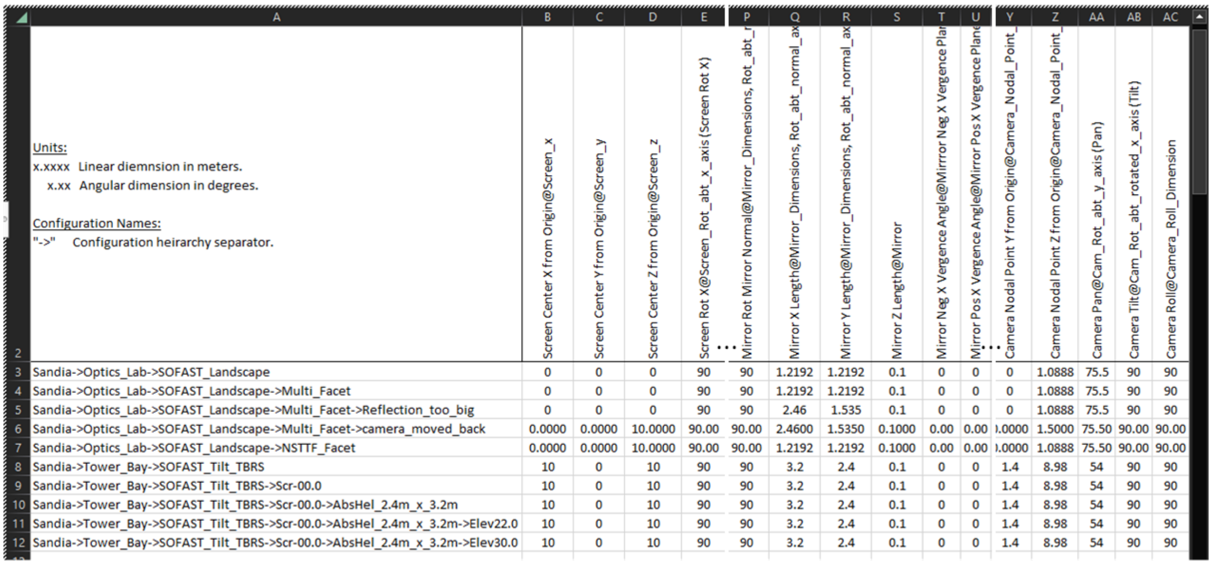
Figure 6. *(a) Feature Tree. (b) Configuration Tree.*

3.2 Tool Characteristics

The tool incorporates organized feature trees, multiple configurations with systematic naming, and the use of design tables. These features enable study of a variety of design aspects, such as exploring if future setups are feasible space constraints, and determining the largest mirror size allowable for a given design. SolidWorks feature names are chosen carefully for documentation and ease of use, with clear organization as can be seen in Figure 6(a) showing the folders in the Feature Tree, and concise feature names. A systematic naming scheme is defined for assemblies, parts, features, and dimensions, making the model more accessible. By following several special design practices such as these, it allows us to take advantage of, and make the tool more useful.

This tool also supports multiple configurations, which include a systematic naming scheme as seen in Figure 6(b), supporting representation of multiple setups, multiple mirrors, and exploration of design trade-offs. By utilizing SolidWorks built in configuration manager, we can easily switch between varying parameters within one model, and without erasing prior parameters/setups of interest.

Figure 7 shows a portion of the design table defining a metrology system model with multiple configurations. Design tables specify key parameter values in both the abstract and concrete model. They show each configuration present in the part or assembly in the first column, the part's features in the first row, and the corresponding dimensions for each configuration in the remaining rows. The design table provides direct access to the primary dimensions specifying a layout in one interface. This allows specification of multiple configurations in bulk and multiple parameters simultaneously, avoiding tedious navigation to individual dimensions, which can be both time-consuming and confusing. This ensemble of design features has enabled us to apply SOFAST to a broad range of complex problems, some of which incorporate multiple configurations per setup.



Units:
x.xxxx Linear diemnsion in meters.
x.xx Angular dimension in degrees.

Configuration Names:
"->" Configuration heirarchy separator.

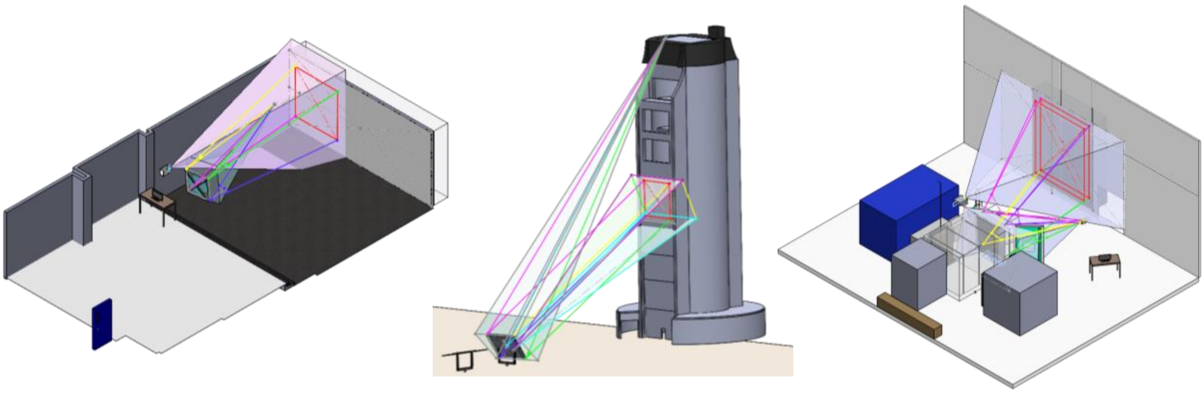
	A	B	C	D	E	P	Q	R	S	T	U	Y	Z	AA	AB	AC
2		Screen Center X from Origin@Screen_x	Screen Center Y from Origin@Screen_y	Screen Center Z from Origin@Screen_z	Screen Rot X@Screen_Rot_abt_x_axis (Screen Rot X)	Mirror Rot Mirror Normal@Mirror_Dimensions, Rot_abt_r	Mirror X Length@Mirror_Dimensions, Rot_abt_normal_ax	Mirror Y Length@Mirror_Dimensions, Rot_abt_normal_ax	Mirror Z Length@Mirror	Mirror Neg X Vergence Angle@Mirrror Neg X Vergence Plar	Mirror Pos X Vergence Angle@Mirror Pos X Vergence Plane	Camera Nodal Point Y from Origin@Camera_Nodal_Point_	Camera Nodal Point Z from Origin@Camera_Nodal_Point_	Camera Pan@Cam_Rot_abt_y_axis (Pan)	Camera Tilt@Cam_Rot_abt_rotated_x_axis (Tilt)	Camera Roll@Camera_Roll_Dimension
3	Sandia->Optics_Lab->SOFAST_Landscape	0	0	0	90	90	1.2192	1.2192	0.1	0	0	0	1.0888	75.5	90	90
4	Sandia->Optics_Lab->SOFAST_Landscape->Multi_Facet	0	0	0	90	90	1.2192	1.2192	0.1	0	0	0	1.0888	75.5	90	90
5	Sandia->Optics_Lab->SOFAST_Landscape->Multi_Facet->Reflection_too_big	0	0	0	90	90	2.46	1.535	0.1	0	0	0	1.0888	75.5	90	90
6	Sandia->Optics_Lab->SOFAST_Landscape->Multi_Facet->camera_moved_back	0.0000	0.0000	10.0000	90.00	90.00	2.4600	1.5350	0.1000	0.00	0.00	).0000	1.5000	75.50	90.00	90.00
7	Sandia->Optics_Lab->SOFAST_Landscape->NSTTF_Facet	0.0000	0.0000	10.0000	90.00	90.00	1.2192	1.2192	0.1000	0.00	0.00	).0000	1.0888	75.50	90.00	90.00
8	Sandia->Tower_Bay->SOFAST_Tilt_TBRS	10	0	10	90	90	3.2	2.4	0.1	0	0	1.4	8.98	54	90	90
9	Sandia->Tower_Bay->SOFAST_Tilt_TBRS->Scr-00.0	10	0	10	90	90	3.2	2.4	0.1	0	0	1.4	8.98	54	90	90
10	Sandia->Tower_Bay->SOFAST_Tilt_TBRS->Scr-00.0->AbsHel_2.4m_x_3.2m	10	0	10	90	90	3.2	2.4	0.1	0	0	1.4	8.98	54	90	90
11	Sandia->Tower_Bay->SOFAST_Tilt_TBRS->Scr-00.0->AbsHel_2.4m_x_3.2m->Elev22.0	10	0	10	90	90	3.2	2.4	0.1	0	0	1.4	8.98	54	90	90
12	Sandia->Tower_Bay->SOFAST_Tilt_TBRS->Scr-00.0->AbsHel_2.4m_x_3.2m->Elev30.0	10	0	10	90	90	3.2	2.4	0.1	0	0	1.4	8.98	54	90	90

Figure 7. *Design Table.*

4. Discussion

We have been able to use the tool to design successful reflection-based metrology layouts for multiple testing scenarios with varying equipment, varying sizes and positions, and in various environments. Some of these are shown below in Figure 8.

The tool was designed to be openly available for public use, so those who are interested can see how SOFAST or other deflectometry measurements could work in their space. Its general design also enables it to be applied to other reflection-based metrology systems. The tool will be available in OpenCSP; if interested send inquiries to OpenCSP@sandia.gov.



(a) (b) (c)

Figure 8. *(a) Compact SOFAST Portrait setup in Sandia NSTTF Optics Lab. (b) SOFAST Tower setup at Sandia NSTTF. (c) SOFAST Thermal setup at CFV Labs.*

Data availability statement

The design tool will be available as part of OpenCSP. Inquiries to OpenCSP@sandia.gov.

Author contributions

Felicia Brimigion contributed software, investigation, and review & editing. Randy Brost contributed conceptualization, software, investigation, design testing, funding acquisition, project administration, and writing. Braden Smith contributed software and data curation.

Competing interests

The authors declare no competing interests.

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