TopAct: Automated Translation from CAD to Combinatorial Geometry for Radiation Transport Analysis

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Modeling of complex three-dimensional engineered systems in the standard radiation transport tools MCNP and TART has traditionally been inhibited by geometry concerns. Most of these systems are designed in the framework of a commercial Computer Aided Design (CAD) package, but the geometrical paradigms used in these products are fundamentally different from the Combinatorial Geometry (CG) framework used in the radiation transport codes. Engineers at Raytheon Missile Systems have developed an automated system for bridging the gap between CAD and combinatorial geometries; it is named TopAct, for "Translation Optimization for Part-wise Adaptive Combinatorial Transport". TopAct has been demonstrated to provide highly accurate, efficient CG representations of real-world parts designed in the ProEngineer CAD system. TopAct thus enables substantial cost savings in the production of radiation transport geometry models, along with attendant benefits in the complexity and accuracy of these models.

I. Introduction

THERE exists a disconnect between the ability to design and model complex physical systems in Computer Aided Design (CAD) systems such as ProEngineer[1] or Solidworks[2] and combinatorial geometry (CG) based radiation transport (RT) codes such as MCNP[3], MCNPX[4], and TART[5]. The RT codes do not read CAD files directly yet they are often used to analyze complex systems that are first designed on a CAD system. A tremendous amount of the detail that is incorporated into the CAD models is discarded for the RT model. The simplification goes well beyond that which is done to prepare similar systems for finite element mechanical analysis. When the time comes to create a RT model the CAD model is discarded, useful only for supplying dimensioned drawings from which the design is reconstructed by hand. This handcrafted, grossly simplified model might take weeks or months to create. This laborious process leads directly to stretched schedules, increased project costs, and inaccurate predictions. The radiation analysis also significantly lags the design process. By the time the analysis is complete it might be too late for the results to be efficiently (if at all) incorporated into the system.

Frustration with the status quo begat a successful effort to develop a system to automatically convert CAD models into CG models for RT codes. The system, Translation Optimization for Part-wise Adaptive Combinatorial Transport (TopAct), retains as much of the detail in the CAD model as is desired, is very fast, and easy to use.

TopAct provides an end-to-end translation capability. It accepts as input part files in the standard STEP format common to most of the popular CAD products. It can also accept IGES files and parasolids. Using a pre-processor developed as a part of the Adaptive Modeling Language (AML[6]) development environment licensed by Technosoft, Inc., STEP files are read in and analytical surface data are extracted. TopAct uses this data to compute an efficient zoning statement for part geometry and any void space in the model. The final optimized form of the zoning statement and surface prescriptions are output in both MCNP and TART formats; tools exist in either code system to validate the model by inspection.

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II. The Translation Process.

The radiation transport analysis requires that one be able to precisely and accurately track a particle through a geometry, applying material interaction physics as the particle traverses space. This is best done using combinatorial geometry to describe the system. The CG system defines space in terms of infinite surfaces; a simple box is defined by six infinite planes. Unlike in CAD systems, the space outside of the box must also be defined: all of space is defined in a CG system. TopAct is unique in its ability to convert a CAD model into an identical CG model. This capability is the result of the development of proprietary patent pending algorithms.

A perfect translator would require nothing more than a single click on a button to translate an entire system. TopAct is not yet the perfect translator. As with preparing a CAD model for Finite Element Analysis, judicious simplification is usually necessary. Details such as screw holes, threads, fillets and rounds should be removed. Because the space that they occupy (and the mass for which they account) is typically very small they can usually be omitted. Screw holes are usually filled with a screw, so simply filling in a screw hole simplifies the model without sacrificing any accuracy. The analyst needs to judge which simplifications are permissible given the design intent for the system and the analytical accuracy that is required.

A process that is not typically done for other analysis packages but that is occasionally needed for TopAct translation is dividing the part/assembly into multiple segments. This is to ensure that memory demands remain reasonable for desktop computers. In addition, a single, complex part can consume all addressable memory and require an additional, slow, processing step. Such a case is detailed below.

Proper preparation of the CAD model for translation is crucial to the success of a translation. Good STEP or IGES files can make the rest of the translation process almost as simple as starting TopAct and pressing Run. However, translating an entire complex assembly in one step can strain or overwhelm computer resources and complicates troubleshooting. The user can choose to work on one CAD file at a time or on multiple files. Each part or group of parts that is loaded into TopAct can be rendered as a wireframe or as a solid. This initial inspection checks that the parts were exported properly from the CAD program. Figure 1 diagrams the translation process, which begins with the CAD files. The flowchart assumes STEP files. The process is identical for IGES files.

The translation process is controlled via a GUI, shown in Figure 2. The first step is usually to draw the part or assembly as has been done in Fig. 2. Errors at the CAD program level are often detectable from viewing the part(s). If visual inspection of the models does not reveal any defects then translation may commence. The initial processing step checks the quality of the parts and alerts the user to problems. In its current configuration a ‘Run All’ button runs the part files through the ‘Preprocess’, ‘Parse’, ‘Rough’, and ‘Assemble’ routines. The optional ‘Holefill’ process randomly places a large number of points (the number is user defined) in the geometry and tests whether the position at which the point resides has been defined in the model. Undefined locations are saved and appended to the geometry. The process continues until the number of undefined points reaches zero or the user stops the process. As noted in Fig.1, the ‘Optimize’ function is usually left as a last step. This function reduces the number of cells in the RT file and increases the efficiency of the analysis runs. Both ‘Holefill’ and ‘Optimize’ can be time consuming; but, they can be forced to terminate early and the benefits of the completed work are retained.

The translation process was timed for the part shown in Figure 2. For this fairly complex part the ‘Preprocess’ step took 6.25 m on a 2.5 GHz, Pentium 4 PC. The parse and rough steps required 1.25 and 0.5 m, respectively. The ‘assemble’ and ‘create MCNP input’ functions required less than 1 s. The time required to prepare an input deck with 108 surfaces and 307 cells was 7 minutes. Going back and using the holefill process on the same part (with the default 500,000 random points) for 25 iterations took 10 m. Figure 3 shows how the number of undefined points varied with the number of iterations. Also shown in Figure 3 is the holefill process for an overly complex part, labeled ‘OBA’, that exceeded the ‘Preprocess’ step’s memory allocation. The holefill process finished the job that the ‘Preprocess’ function began. Each iteration for ‘OBA’ required 3.4 m. Subdividing the part would have been more time efficient. The plot demonstrates that the greatest benefit of the holefill process is reached in just a few iterations, the number of which is under user control.

After optimization the surface count remained the same but the number of cells dropped from 307 to 229. The holefill and optimization process made no difference in the number of particles lost in the initial MCNP run. Of 100 million particles run through the geometry 24 got lost in the optimized deck and 26 got lost in the un-optimized deck. For this particular part the holefill process was not needed and the optimization process did not introduce any errors into the geometry. The benefit of the optimization process appeared in the run times. The optimized deck was 15% faster than the un-optimized deck. Particles lost in the initial translation are of little concern for reasons explained below.

The initial CG file is in TART format to permit quick inspection with the utility tartcheck.exe, which is launched from within TopAct. This utility permits not only rapid 2D and 3D visual inspection but can also quickly find

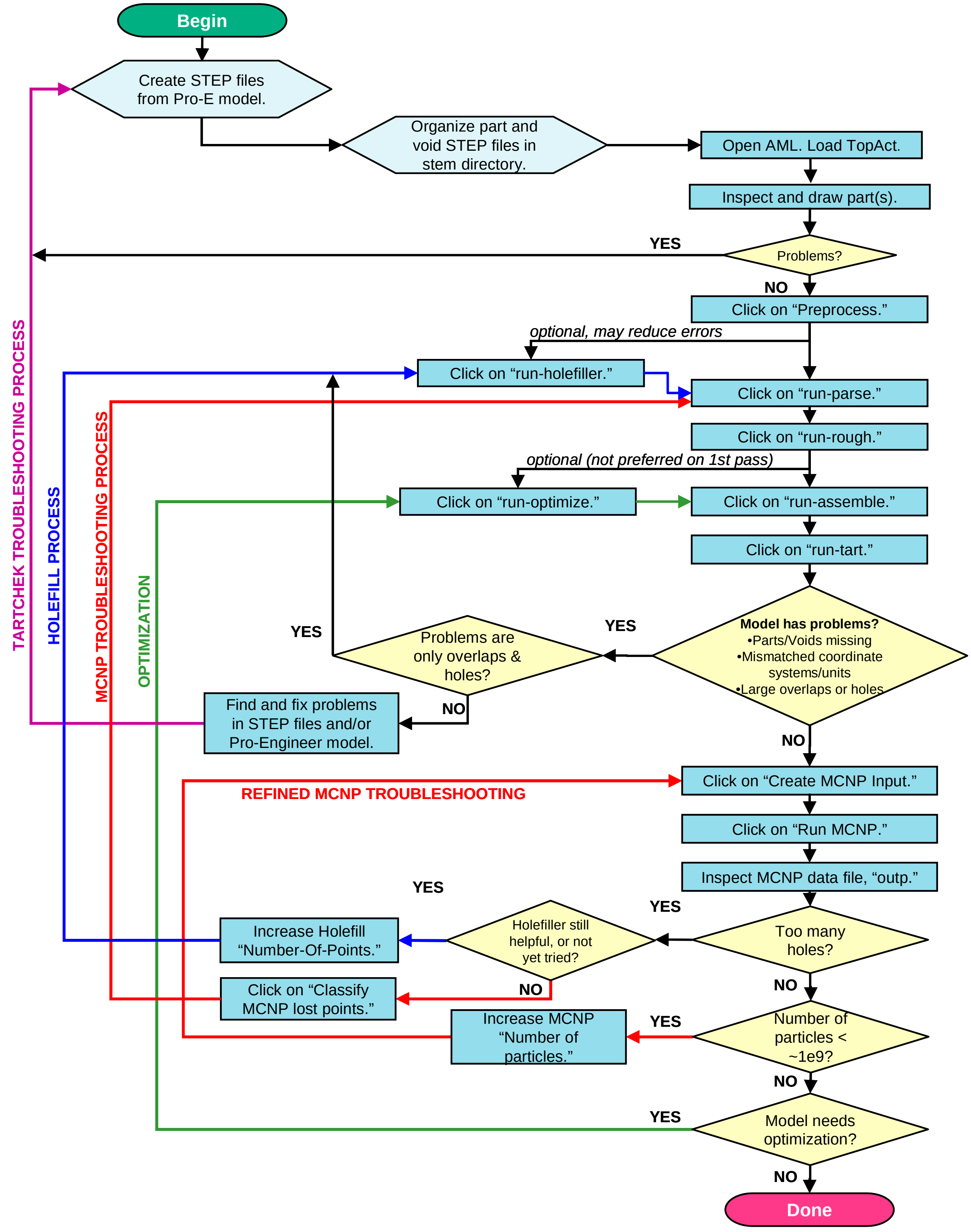
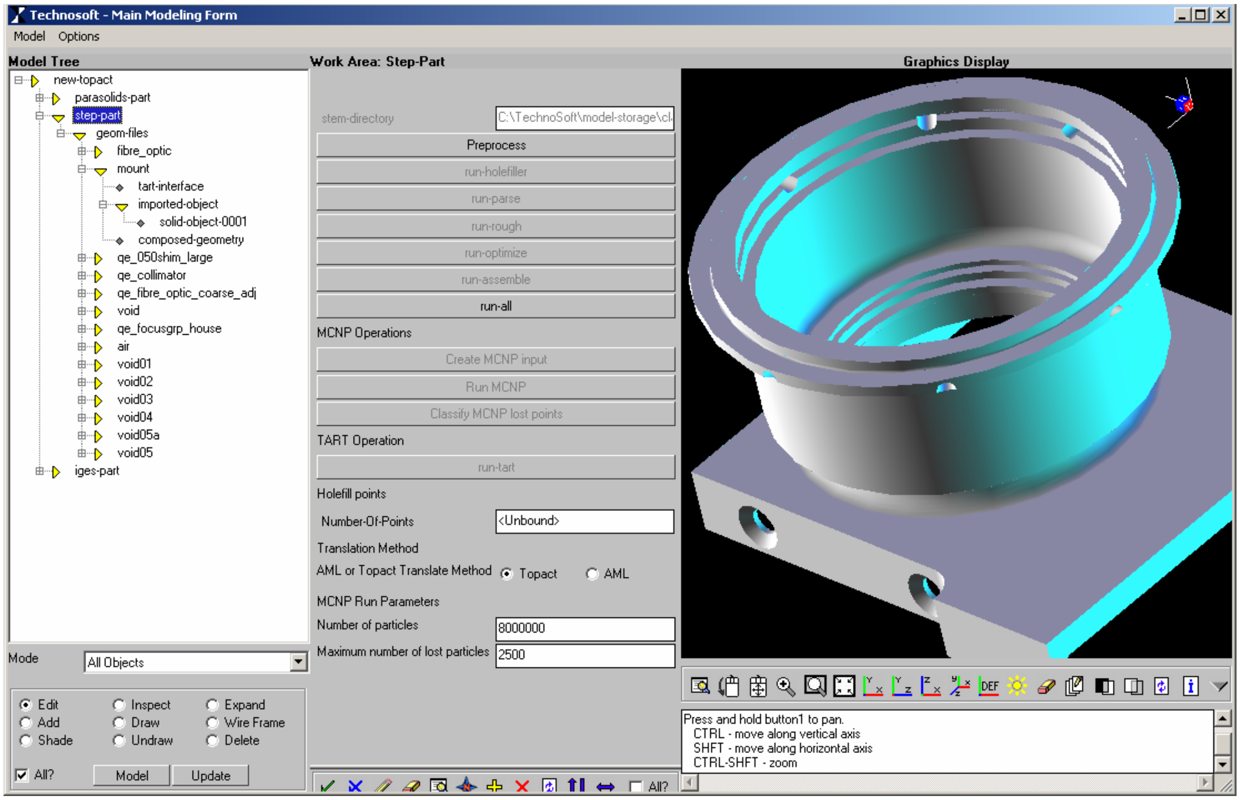


Figure 1. Flowchart of TopAct translation process.



stem-directory: C:\TechnoSoft\model-storage\cl

Number-Of-Points: <Unbound>

Translation Method

AML or Topact Translate Method: ● Topact ○ AML

Number of particles: 8000000

Maximum number of lost particles: 2500

Mode: All Objects

● Edit

☑ All?

☐ All?

Press and hold button1 to pan.
CTRL - move along vertical axis
SHFT - move along horizontal axis
CTRL-SHFT - zoom

Figure 2. TopAct Graphical Use Inerface. Part tree on the left. Process buttons in the center. Part can be drawn in wireframe or shaded.

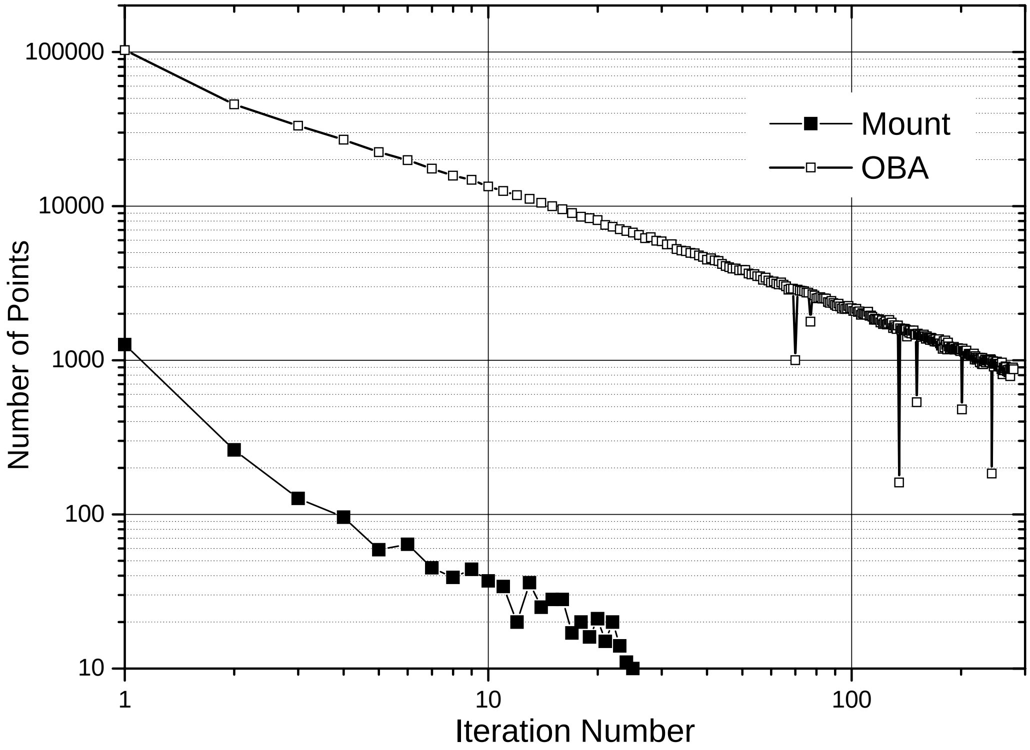


Figure 3. Number of points found during the ‘holefill’ operation versus number of iterations for two different parts. The ‘OBA’ is should have been divided into two or three sections for improved initial translation. At each iteration 500,000 points were randomly placed in the part.

defects in the geometry via ray tracing. A button on the TopAct GUI converts the TART formatted file into an MCNP input deck. A freshly minted translation almost always needs some refinement prior to RT analysis. TopAct launches MCNP to find and report small errors (lost particles) in the geometry. TopAct then uses the lost particle positions and directions to refine the model. In this iterative process the user controls the number of particles to track through the geometry and the maximum number of lost particles to tolerate before stopping the MCNP run. Users can also open and edit the MCNP file to alter source parameters if so desired. While an ideal TopAct generated MCNP model will lose track of zero particles, it may happen that tolerance limits prevent TopAct from reducing the number to zero. The number can be reduced to zero manually with small adjustments. A typical error is a cylinder in line contact with a plane or another cylinder. A tiny overlap in one model was corrected by changing the radius of one cylinder from 0.1111250000000000007E+01 cm to 0.1111249999990000E+01 cm, a change of only 1E-11 cm. If losing any particles is unacceptable, the parameters to change are usually easy to determine and a model can be perfected in a few hours.

If material density and composition is present in the CAD file it is incorporated into the MCNP and TART files. If the material information is not in the CAD file a small text file is created for each part. The user can then enter the density and atomic composition into the material file prior to the ‘Assemble’ step and have the material information incorporated into the MCNP and TART files.

The freshly created MCNP files require no modification to run. However, for any specific analysis the user must modify the source definition.

III. TopAct Capabilities

A demonstration of the accuracy of TopAct translations is shown in Figure 4. For this example, the secondary mirror part depicted in Figure 5 was translated into MCNP format, and the MCNPX code was used to trace rays through the part. The path length data generated by MCNPX were used to compute the total material volume of the part. Using the specified density of the material, the total weight of the part was computed. Figure 4 compares this Monte Carlo weight approximation to the deterministic computation performed by ProE on the original CAD part. It is observed that the error in the weight decreases log-linearly as the number of samples increases. This is consistent only with geometrical representations of the part that are identical to within the lowest error projection of the curve. Therefore in this case the translation is accurate to at least one part in 1000, and very probably one part in ten thousand.

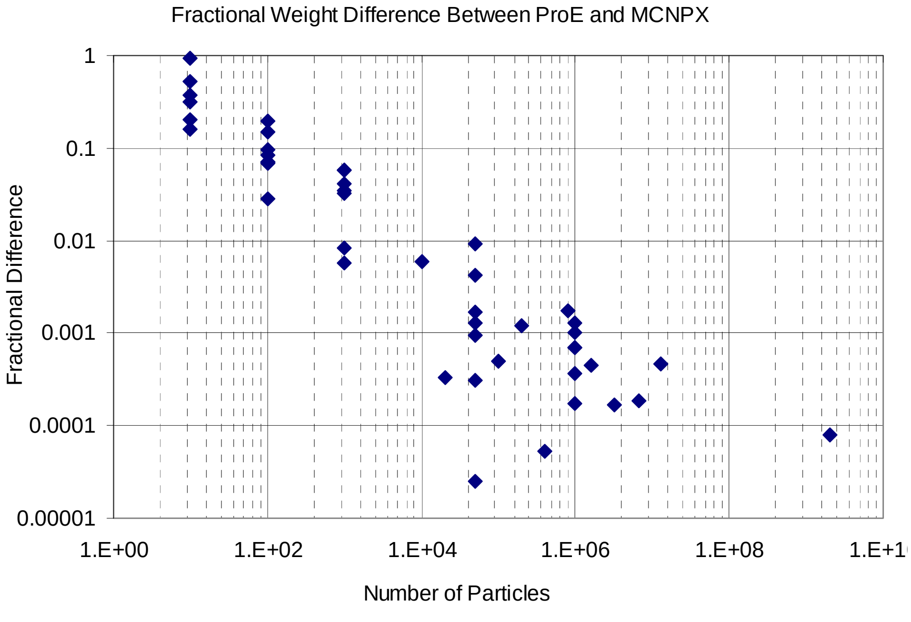


Figure 4. For the mirror part shown in Figure 5, this chart shows how the difference in calculated weight between ProE and MCNP decreases with the number of particles run in the Monte Carlo MCNP code. Multiple runs with the same number of particles but different random number seeds demonstrates the variability inherent in Monte Carlo calculations.

Weight/volume comparison between the CAD model and the RT model is used to ensure that critical parts or materials are accounted for and to gauge the degree of simplification that took place in creating the RT model. It is a non-visual means of verifying that the translation to CG geometry is accurate. An example is computation of the mass of fissile material in the nuclear reactor GODIVA, Figure 6. Agreement between the ProE and MCNP models to better than 0.006% was achieved with 1 billion particles.

The ability of TopAct to create accurate, high resolution radiation transport models greatly

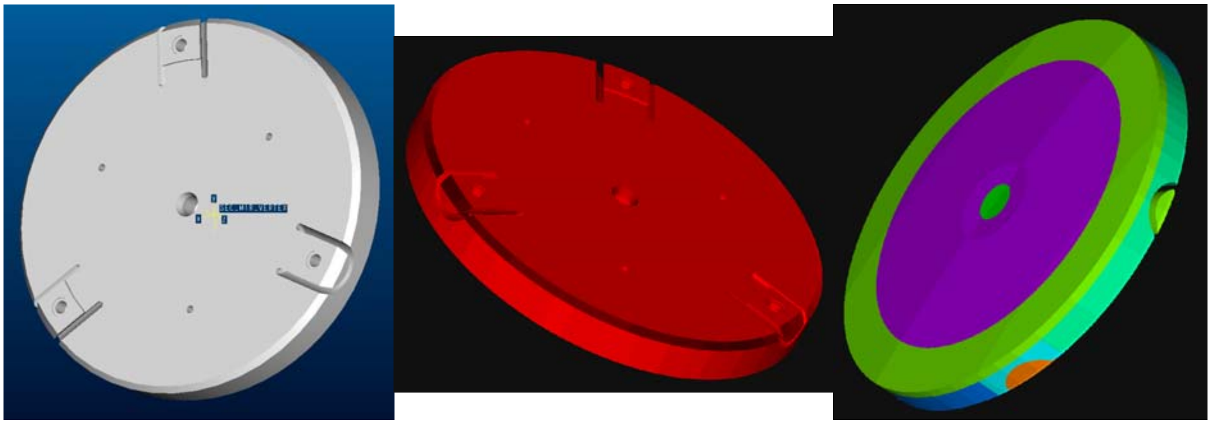
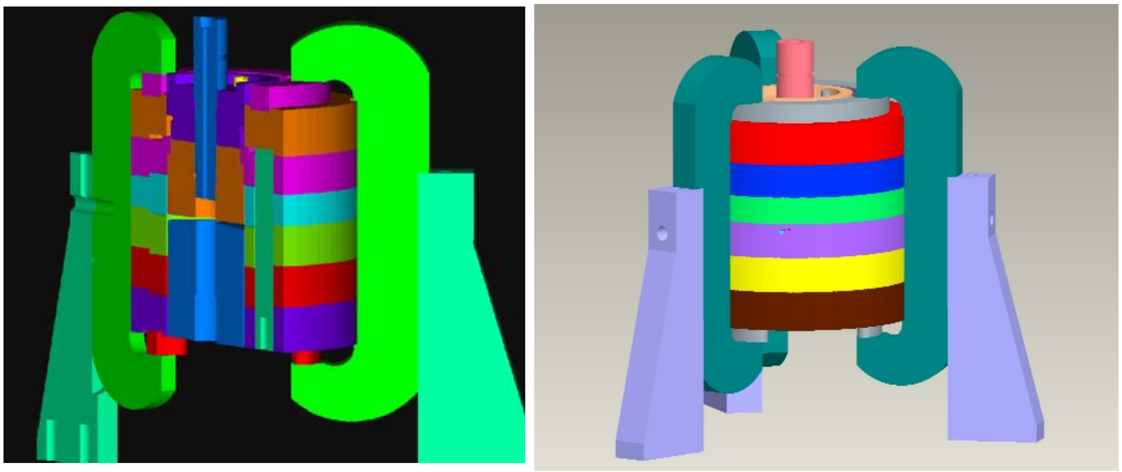


Figure 5. Secondary mirror as rendered in ProEngineer (left) and TART (center and right). All of the features of the CAD representation of the mirror are present in the CG representation. The rightmost picture is shows the front of the mirror. The different colors represent various cells or zones in the CG model.



(a) (b)

Figure 6. Two representations of the nuclear reactor GODIVA. Figure 6a, is a cut-a-way of the RT model. Figure 6b is the original CAD model. All of the details of the original model were retained.

enhances the ability of analysts to accurately predict radiation doses to spacecraft. Doses can be accurately mapped throughout a volume of interest, such as an electronics box. Figure 7 shows an electronics box as rendered in TART. This is a large box that contains 20 circuit cards. For the radiation analysis 5 sets of 9 Si discs were placed in regular 3 x 3 array on evenly distributed among 5 of the 20 cards. The Si discs function as dosimeters. The simulation used approximately 600 million protons isotropically emitted from a sphere surrounding the box and a typical AE8 proton energy spectrum. The resultant doses are shown in Figure 8. This figure clearly shows that parts at the bottom of the box receive 6 to 8 times the dose of parts at the top of the box. As might be expected, doses at the ends of the box are higher than at the center. Prior to the implementation of TopAct, this box would have been modeled in such a simple fashion that only one data point would have been taken.

A direct comparison between a simple model and high fidelity TopAct generated model on a another electronics box showed that the dose varied within the electronics box by a factor of two. More importantly, the high fidelity TopAct derived model predicted half the dose of the simple model. This accuracy of dose prediction has great potential benefits for spacecraft. Shielding can be minimized and more strategically placed. Weak spots in shielding can be found and corrected. Sensitive parts can be placed in lower dose regions.

TopAct also assists in determining whether shield design goals have been met. The shielding for a proposed weather satellite was modeled for this purpose. During the analysis it was discovered that the design was not complete when a pair of small holes were found in the shield. Figure 9 is a visualization of the distribution and energy of mono-energetic protons that penetrate the shielding. The protons originate in the detector volume that is being shielded. The length of the vector is proportional to the proton energy after passing through the shielding. It can be seen that some directions are better shielded than others. Thanks to the high fidelity of the RT model such variations in shielding are known to be real rather than artifacts of simplifications made to the system in order to generate a RT model. The RT models are capable of detailed tracking of particles throughout the system that can be used to fine tune the shielding design to a degree unthinkable in a hand-made model.

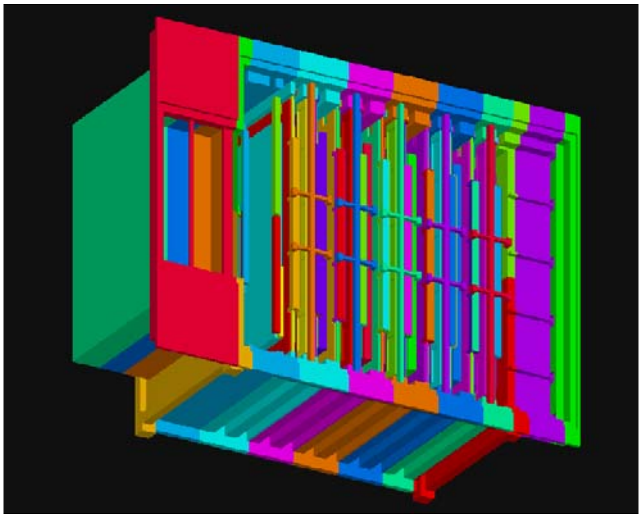


Figure 7. Electronic box with lid removed. The box contains 20 circuits cards and 10 heatsinks. This rendering is from TART. The colors are an artifact of the zoning process.

In addition to the much improved analyses TopAct results in significant time savings. It takes only a matter of days to go from a CAD model to a high fidelity RT model. Changes made to the ProE model can be rapidly incorporated into the RT model without the need for complete retranslation; only modified parts must be updated. Thus, designs and revisions to designs can be accurately analyzed without causing schedule delays. The system designers and analysts can work in parallel, much as they do in other analytical fields.

IV. Conclusions

The TopAct code is an accurate and efficient means of computing CG representations of engineered parts, components and systems. TopAct translations have been demonstrated to be able to achieve accuracies of better than 99.9% of net part weight. Implementation of the TopAct software can result in cost-savings and design improvements stemming from interdisciplinary collaboration throughout the design cycle.

The ultimate capability of TopAct is emergent; it allows radiation transport analysts to fully participate with mechanical designers as a system design is evolved. When translations are performed by hand, detailed transport models are typically produced only very late in the cycle, as the expense involved precludes multiple iterations. This frequently leads to late, inelegant design patches when transport calculations reveal system shortcomings. Because TopAct can reduce translation time by as much as two to three orders of magnitude, it allows designers and analysts to evolve their high-fidelity models in parallel, and weaknesses to be discovered early in the design phase. This cooperative arrangement often leads to more elegant, efficient, superior delivered components and systems.

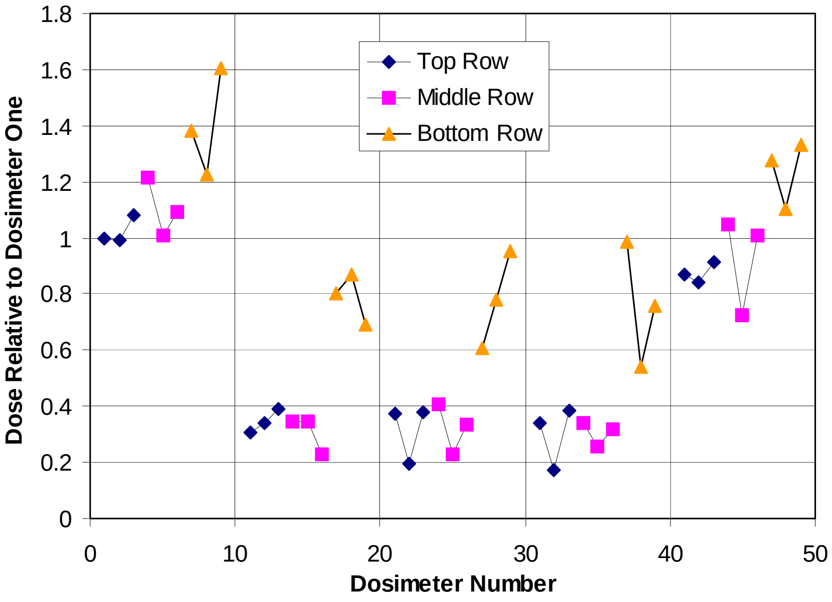


Figure 8. Dose due to isotropic protons as a function of position within the box of Fig. 7. Dose is normalized to first dosimeter. Nine dosimeters per board were on five boards. Dosimeters 1-9 and 41-49 were at the ends of the box, 21-29 were in the center. The rest were midway between the ends and the center.

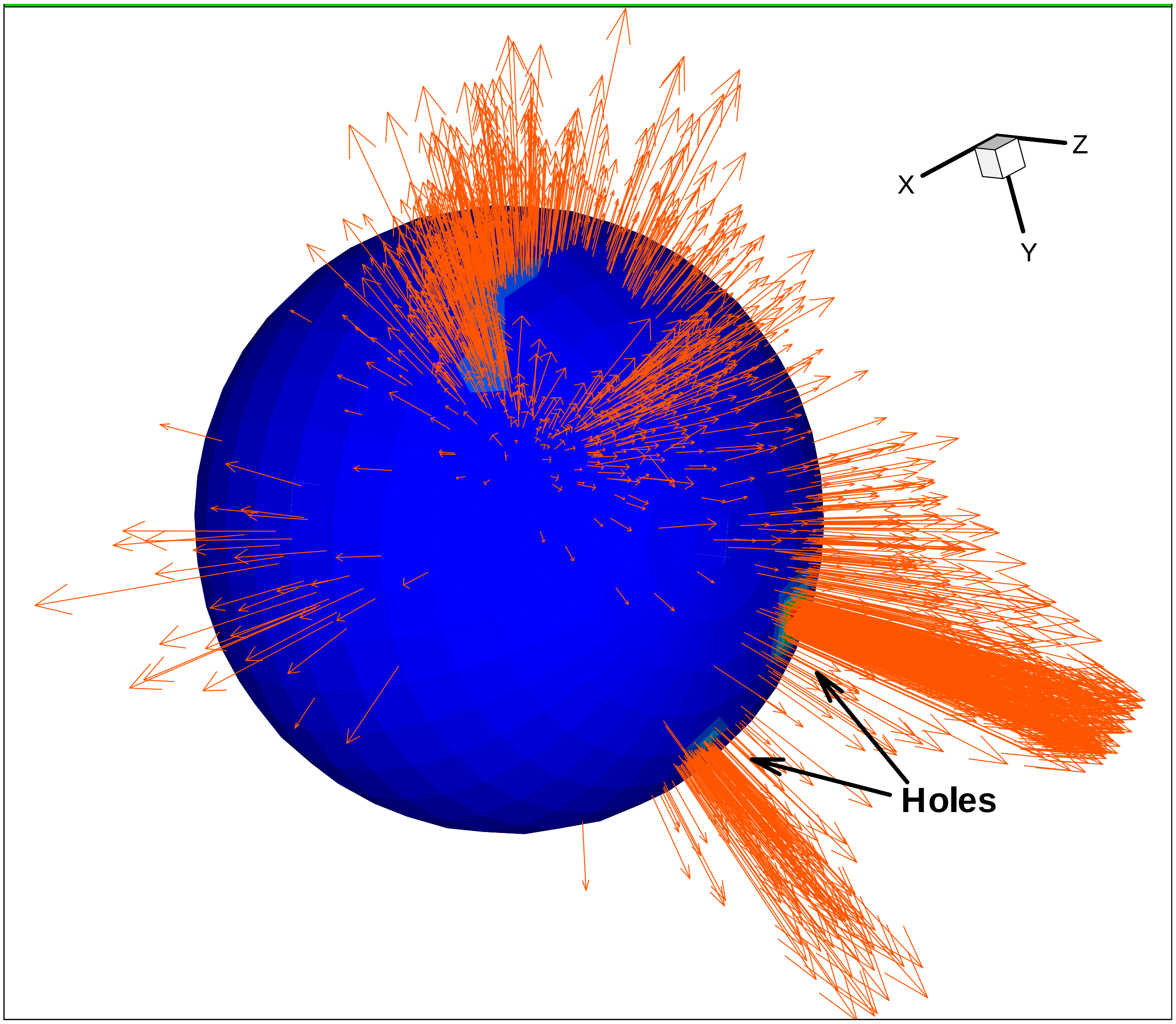


Figure 9. Vector plot of protons originating at detector that pass through radiation shield. The vector length is proportional to proton energy at the sphere surface. Two small holes were found in the shield. A region of thinner shielding is visible at top center.

References

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