High Fidelity Transport in Complex Geometry Using Logical Combinatorics in TopAct™

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INTRODUCTION

Inaccuracies in Monte Carlo transport analyses are typically attributed to statistics, material properties, source specification, and detector property assumptions. However, geometrical simplification of real world complex systems can lead to errors that are just as significant. Engineers at Raytheon have developed a translation system called TopAct™ which addresses many issues inherent in the use of complex geometry. TopAct allows automated translation of high fidelity Computer Aided Design (CAD) models into the format needed by most of the industry standard Monte Carlo nuclear transport tools. These computer codes include MCNP [1], ITS [2], NOVICE and GEANT4 [3].

Other techniques (e.g. [4]) seek to enable the use of CAD geometry in transport codes by interfacing the raytracing tool with the CAD engine in order to make direct geometrical queries with the native CAD geometry model. In contrast, TopAct is a geometrical preprocessor which delivers a complete geometry deck in the native surface-based combinatorial geometry that the transport codes use for speed-optimized raytracing. This enables the transport engineer to take advantage of decades of work that LANL, SNL and LLNL have invested in minimizing the time it takes to compute the scattering path that a ray takes in transiting a model.

DESCRIPTION OF THE ACTUAL WORK

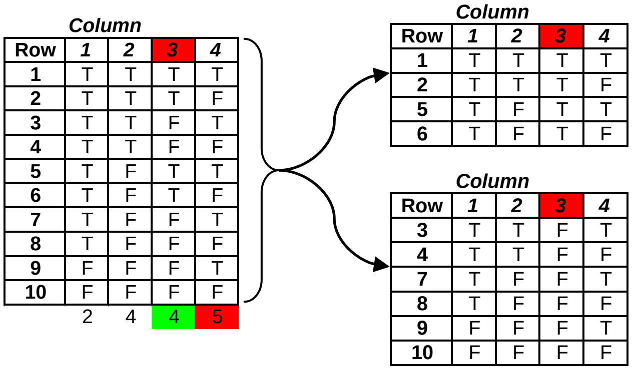
Translation Procedure

TopAct begins with separate CAD geometry files for each part in a physical system. Each part file must contain a mechanical component or group of components together consisting of only a single material, and be described with regard to a consistent, system-level coordinate and units system. The part files may be imported in STEP or Parasolids formats; these formats are supported by most of the commercial CAD software systems. If material information is available from the CAD system it is also read in as a part of the importation step.

The part files are individually queried for all surface prescriptions that bound the part. These surface equations are generalized to the unbounded analytic form preferred by the transport codes. Because TopAct prepares output in the native format of the transport codes, only the unbounded analytic surface types supported by those codes are permitted in the TopAct translation scheme. However, TopAct does provide tools for fitting several classes of spline surfaces (e.g. revolved and projected spline curves) with the supported analytic surfaces. Subsequently, TopAct expands the analytic surface list corresponding to each part by computing likely ambiguity surface candidates using a heuristic method. Ambiguity surfaces are extra surfaces necessary to disambiguate certain types of geometry; they will not be present in a boundary surface list (nor in a typical CAD model) for a part since they as a rule do not constitute an interface between the part and the space surrounding it. TopAct automatically generates and subdivides a part constituting the vacuum or airspace in and around the system. This series of parts is translated in the same manner as the material parts since many of the transport codes require all of space to be positively defined.

Subsequently, a pair of truth tables is generated for each part by considering geometric point locations in and around its constituent material. Candidate points are determined by computing coordinate locations from intersections of triples of surfaces, and offsetting those locations by a small delta in the directions normal to each surface. These points can be computed to lie inside or outside the part; each set of points thus differentiated becomes a separate truth table. The tables are filled out by comparing each point to each of the analytic surfaces that comprise the part, as each surface is defined as having an inside (T), and an outside (F). The transformation of the translation problem from one of multi-dimensional geometry to one of pure logic (truth tables) represents a novel approach to the solution of this problem. The chief advantage of this solution is that the engine for determining the prescription of zones in combinatorial form does not change as new classes of surfaces are introduced; if the user has a combinatorial raytracer that uses 7th order polynomial surfaces, TopAct can accommodate that desire by the mere addition of a point testing algorithm for that class of surface; no change to the core translation engine is required.

The resulting truth tables are iteratively simplified by the elimination of redundant or unnecessary rows (corresponding to individual points, each of which will represent a zone region in the optimized geometry), columns (corresponding to the analytic surfaces), or individual table entries. In the currently implemented scheme, a column of a complementary pair of truth tables is selected to best bisect the T table into two sub-tables of approximately equal complexity, as depicted in Figure 1. The four resulting tables can be further simplified as above via the elimination of redundant or unnecessary data. This procedure is repeated iteratively until all the resulting truth tables meet a criterion for simplicity. The final set of T truth tables can be concatenated to form the zoning statement for the part. The F tables are used only for bookkeeping, and to test the necessity of the various elements (rows, columns, table entries) of the T tables; they can thus be discarded.



	Column			
Row	***1***	***2***	***3***	***4***
1	T	T	T	T
2	T	T	T	F
3	T	T	F	T
4	T	T	F	F
5	T	F	T	T
6	T	F	T	F
7	T	F	F	T
8	T	F	F	F
9	F	F	F	T
10	F	F	F	F
	2	4	4	5

	Column			
Row	***1***	***2***	***3***	***4***
1	T	T	T	T
2	T	T	T	F
5	T	F	T	T
6	T	F	T	F

	Column			
Row	***1***	***2***	***3***	***4***
3	T	T	F	T
4	T	T	F	F
7	T	F	F	T
8	T	F	F	F
9	F	F	F	T
10	F	F	F	F

Fig. 1: Example Truth Table Bisection

The end result of the truth table optimization is an optimized transport code prescription for each part. It is frequently unappreciated that the transport code geometry input format has a one-to-one correspondence with a truth table wherein each row is a logically convex region of space bounded by a number of signed surfaces corresponding to the columns of the table. Those surface signs correspond to the logical value in each entry of the truth table, and any undefined entries mean that the surface in question does not bound the corresponding region. These prescriptions are assembled together and output in the formats for each of the supported tools. This guarantees that the geometry described is identical in each of the various formats; this can be very helpful when validating transport techniques and applications.

Figure 2 depicts the results of the truth table optimization algorithm. To produce these results three different parts (having 64, 198, and 218 boundary surfaces in the original CAD model) were translated via TopAct, using a two-level optimization procedure. In the first level, truth tables are iteratively bisected until a simplicity criterion (number of columns) is met. The simplified truth tables are optimized to remove rows, columns, and individual entries as discussed above. In the second level of optimization, the simplified optimized truth tables are serially recombined and subsequently re-optimized by the same algorithm. It has been found that the bisection algorithm provides a highly optimized solution in a very time-efficient manner, and that while gains are still significant via the second level approach, it is frequently not worth the processing time. The figure shows that a two orders of magnitude decrease in the number of zones (cells in MCNP parlance) is typical in parts of the represented complexity. These results were computed in a matter of seconds on an unremarkable laptop running windows XP for the first level optimization and on the order of 10 minutes per model for the second level optimization.

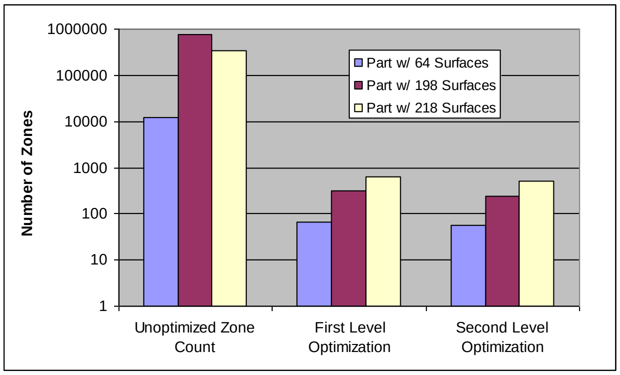


Fig. 2: Example Optimization Results

As there is no guarantee that that the translation process begins with a complete point set to uniquely and exhaustively identify all regions of space in the model, the TopAct algorithm enables the querying of the model via ray tracing to determine if there are gaps or overlaps in the system. TopAct has its own raytracer, but can also run MCNP and post process the results in order to cull out the requisite data that specifies where in the model space a ray was lost. This data is incorporated back into the model, which is automatically recomputed to “heal” the previous defect. TopAct, in fact, has incorporated a scripting tool which allows multiple healing iterations to be performed in an automated fashion.

The final result of a TopAct translation is a complete restatement of the input geometry in each of the native combinatorial surface geometry formats implemented by the previously mentioned transport codes. TopAct also supports a graphical user interface-enabled ability to specify source and tally geometry but only in the MCNP and MCNPX formats. Similarly, TopAct allows the user to specify index offsets and universe specification so that multiple translations can be concatenated together to form larger and more complex system-level decks as needed by the user.

Transport Results

TopAct has been used to do a number of very large translations of complex geometry for space and defense applications [5]. It has been previously shown that

TopAct translations are highly accurate in terms of the geometrical formulation when compared to the original CAD model [6], both in terms of mass and volume preservation. A survey of older Raytheon transport models demonstrated that most constituted between 35% and 50% of the actual system mass. TopAct translations typically represent more than 90% of system mass, thus markedly improving the accuracy of the associated transport analyses. This can lead to reductions in shielding mass and increased design margins.

Figure 3(a) depicts an electronic box represented as a simple parallelepiped with uniform wall thickness as is common practice in industry. Panel (b) shows the TopAct translation of the same box with all the real world complexity, including a stack of three double-sided multi-layer electronics cards. Panel (c) shows the computed dose variation over the top side of the middle card. This MCNP analysis demonstrates the value of high fidelity geometry translation, as the peak dose location on the card is a factor of four lower in dose than the dose computed for the simple box, and the minimum dose location on the card is a further factor of two lower than that. If such an analytical result is available during card layout design the softest parts may be put in locations where they will receive the minimum dose. This can result in lower parts costs and lower shielding mass.


(a) (b) (c)

Fig. 3: Example Transport Results

As mentioned regarding Figure 1, the increased model fidelity does incur a price in terms of longer transport run times in order to develop adequate statistics. In practice it has been determined that when designing complex systems where shielding mass is costly in terms of system design and performance (e.g. space vehicles), extra analysis time is well worth the cost in run time and/or computer power.

CONCLUSIONS

TopAct translation methodology transforms the geometrical translation problem into a logical optimization problem by collecting the boundary surface prescriptions from a CAD model and testing various point coordinate locations in and around the model. The tests are used to develop a truth table that provides a complete representation of the original model in logic space. The truth table model is subsequently optimized to minimize the number of zones that will comprise the output geometry. The resulting transport model is a high-fidelity representation of CAD model geometry ready for use with many of the industry standard Monte Carlo transport codes.

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