

Use of a Hybrid Edge Node-Centroid Node Approach to Thermal Modeling

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A recent proposal submitted for an ESA mission required that models be delivered in ESARAD/ESATAN formats. ThermalDesktop was the preferable analysis code to be used for model development with a conversion done as the final step before delivery. However, due to some differences between the capabilities of the two codes, a unique approach was developed to take advantage of the edge node capability of ThermalDesktop while maintaining the centroid node approach used by ESARAD. In essence, two separate meshes were used: one for conduction and one for radiation. The conduction calculations were eliminated from the radiation surfaces and the capacitance and radiative calculations were eliminated from the conduction surfaces. The resulting conduction surface nodes were coincident with all nodes of the radiation surface and were subsequently merged, while the nodes along the edges remained free. Merging of nodes on the edges of adjacent surfaces provided the conductive links between surfaces. Lastly, all nodes along edges were placed into the subnetwork and the resulting supernetwork included only the nodes associated with radiation surfaces.

This approach had both benefits and disadvantages. The use of centroid, surface based radiation reduces the overall size of the radiation network, which is often the most computationally intensive part of the modeling process. Furthermore, using the conduction surfaces and allowing ThermalDesktop to calculate the conduction network can save significant time by not having to manually generate the couplings. Lastly, the resulting GMM/TMM models can be exported to formats which do not support edge nodes. One drawback, however, is the necessity to maintain two sets of surfaces. This requires additional care on the part of the analyst to ensure communication between the conductive and radiative surfaces in the resulting overall network. However, with more frequent use of this technique, the benefits of this approach can far outweigh the additional effort.

Nomenclature

<i>DT</i>	=	Delta Temperature (Temperature Difference)
<i>ESARAD</i>	=	European Space Agency Radiation Analyzer
<i>ESATAN</i>	=	European Space Agency Thermal Network Analyzer
<i>GMM</i>	=	Geometric Math Model
<i>TMM</i>	=	Thermal Math Model
<i>MLI</i>	=	Multi Layer Insulation

I. Introduction

A proposal for ESA's ExoMARS mission required that all models be delivered in ESARAD and ESATAN formats. The PLUME instrument proposal team opted to use ThermalDesktop for the rapid development of models of the design, accepting that a model conversion would be necessary for future deliveries upon instrument award. This allowed PLUME to take advantage of the benefits of ThermalDesktop's environment and capabilities for faster model generation and trade studies. However, an understanding of the limitations of converting to ESARAD/ESATAN was necessary to avoid using features that had no counterparts in the ESARAD software. One such feature is the use of edge nodes, which is not supported in ESARAD; ESARAD supports centroid based surfaces. The approach described herein was developed to: allow use of edge nodes for faster generation of the conduction network, solve only for the centroid nodes, take advantage of a smaller radiation model, and reduce the overall time necessary to generate and execute the analysis.

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II. Analytical Approach

A sample pair of adjacent rectangular surfaces is shown in Figure 1A with a 1x1 centroid nodal subdivision. Figure 1B shows the corresponding surfaces with a 3x3 edge node subdivision. As seen in the two figures, the centroid nodes are coincident with the middle node of the edge node surfaces. Making these surfaces coincident and merging these nodes makes them identical solution points for the thermal solver. Furthermore, use of edge nodes allows heat to flow from one centroid node to the other through the edge nodes. Moreover, the number of radiation nodes is greatly reduced by using the centroid based surface for radiation, while using the edge node surface for conduction. The centroid based surfaces are hereafter referred to as *Radiation Only Surfaces*, while the edge node based surfaces are referred to as *Conduction Only Surfaces*.

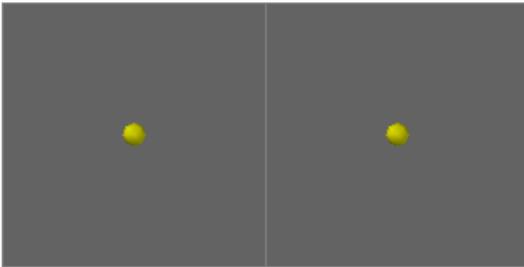


Figure 1A – Centroid Subdivision

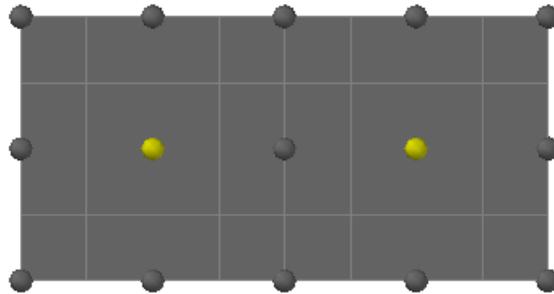


Figure 1B – Edge Node Subdivision

Regardless of nodal breakdown for a uniform subdivision, any surface can be similarly represented; an $n \times m$ centroid subdivision would be coincident with nodes from a $(2n+1) \times (2m+1)$ edge node subdivision as shown in Figure 2.

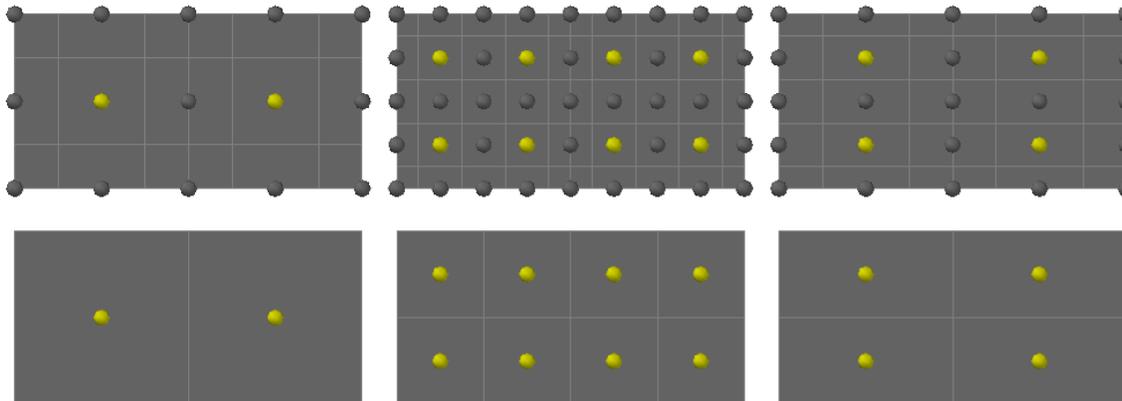


Figure 2 – Centroid Subdivision vs. Edge Node subdivision

Disabling conduction for the *Radiation Only Surfaces* (by either using a zero conductivity material or a multiplier of zero for the thermal conductivity) eliminates any generation of couplings based on those surfaces. To disable radiation for the *Conduction Only Surfaces*, they should be excluded from all Radiation Analysis groups. Furthermore, the capacitance generation should be disabled for the *Conduction Only Surfaces* by selecting a material with a zero density or specific heat or using a zero multiplier for the capacitance. This method lumps all of the capacitance onto the *Radiation Only Surface* nodes and uses these same nodes for radiation calculations.

Lastly, the analyst has the option of allowing the non-centroid nodes to remain in the solution (as thermal only nodes) or to remove them using the supernetwork/subnetwork feature of ThermalDesktop. While this feature will eliminate the non-centroid nodes through the internal matrix reduction algorithm, it may generate a large number of mathematically insignificant linear couplings. For final model deliveries, it is recommended to eliminate these terms.

Use of this approach does however require careful setup on the part of the analyst to ensure that unintended consequences of mis-numbering or mis-assignment are avoided; the solver will likely not catch these errors since connectivity to a boundary could be established by either set of surfaces. Therefore, the procedures for defining the surfaces to use this technique are carefully presented in the next section.

III. Modeling Technique Procedure

To generate a model using this technique, an analyst should follow the outlined sequence carefully for each set of surfaces defined by a common submodel:

1. Generate all centroid surfaces and fully define all surfaces (MLI, thickness, active sides, optical properties, size, location, nodal subdivision, etc.)
 - a. Use thermal conductivity multiplier of 0
 - b. Use capacitance multiplier of 1
 - c. Use Centroid nodes
 - d. Use “Rad” prefix in comment
2. Define all these surfaces as AutoCad Group
3. Copy all centroid surfaces to coincident location
4. For all original surfaces (select by using the Group definition)
 - a. Globally Disable all activity in Radiation Analysis Groups
 - b. Globally Change thermal conductivity multipliers to 1
 - c. Globally Change capacitance multiplier to 0
 - d. Remove MLI from all *Conduction Only Surfaces*
 - e. Add “Cond” to Comment
 - f. Adjust node subdivision to $2n+1 \times 2m+1$ and change to Edge Nodes
5. Merge all coincident nodes
6. Select all nodes (not surfaces!) associated with *Conduction Only Surfaces*. Renumber to 10000 range
7. Select all nodes (not surfaces!) associated with *Radiation Only Surfaces* and renumber to 1000 range
8. Select all nodes in 10000 range (not surfaces!) and renumber to 10000 range (compresses nodes renumbered by step 7)
9. **Optional** Override calculations of nodes by surfaces and place all 10000 range nodes into subnetwork. Enable subnetwork calculations
10. Repeat for next set of surfaces in different submodel...

Details of these steps are expanded hereafter. First, all surfaces should be fully defined using centroid nodes with correct optical property definitions, active sides, thicknesses, materials, etc. It is advised to include a “Rad” prefix to any comments or to use “RadOnly” as the comment for easier identification of these surfaces in the Model Browser. Lastly, set all conductance multipliers to zero and all capacitance multipliers to one to disable conduction calculations and enable capacitance calculations. These surfaces define the surfaces known as *Radiation Only Surfaces*.

Next, copy all *Radiation Only Surfaces* to coincident locations. Defining an AutoCad group before copying makes selection of these surfaces easier. All of these new surfaces should now be modified to become *Conduction Only Surfaces* by removing them from all Radiation Analysis Groups as well as removing all MLI from the *Conduction Only Surfaces*. All conductivity multipliers should be reset to one and capacitance multipliers reset to zero. If possible, a “Cond” prefix added to the comments also helps to identify the surfaces in the Model Browser. The last part of this step is to adjust all surface subdivisions to Edge Node breakdown and increase the subdivisions using $(\# \text{ Edge}) = 2 * (\# \text{ Centroid}) + 1$. At this point, selection/display of the *Radiation Only Surfaces* could be accomplished by selecting the appropriate Radiation Analysis group surfaces from the Model Browser. Similarly, displaying all surfaces and then removing the Radiation Analysis Group surfaces from display allows selection of the *Conduction Only Surfaces*. To display the nodes for the *Conduction Only Surfaces* using this approach, turning on node numbers and then turning them off again will result in the nodes now being visible, so long as the global visibility flag is on.

The next step is to merge all nodes. This establishes the link between the centroid nodes of the *Radiation Only Surfaces* and the coincident edge nodes of the *Conduction Only Surfaces*. Furthermore, it establishes the links between edge node surfaces as the edges are now defined by common nodes for adjacent surfaces. The next step is to renumber the centroid and edge nodes into different ranges for easier identification. To do this, it is best to renumber all nodes associated with the *Conduction Only Surfaces* to a specific range (e.g. 1xxxx). Next, the nodes associated with the *Radiation Only Surfaces* should be renumbered to a different range (e.g. 1xxx). Finally, renumbering the nodes in the 1xxxx range to 1xxx again eliminates gaps and optimizes the numbering. It is

important to only renumber the nodes during these steps, as renumbering a surface will renumber all nodes associated with it and could undo some of the changes made during the process flow. For doing this, it is often easiest to turn global visibility off for surfaces so that only nodes can be selected, although there may be other ways to accomplish this.

The final step is optional, but may be necessary if nodal allocations are limited by contractual obligations. The creation of numerous arithmetic nodes for conduction between the centroid nodes can be eliminated by using the Super-Network feature of ThermalDesktop. If all of the arithmetic nodes are placed into the subnetwork, then only the centroid nodes (Super Nodes) are passed to the thermal model. The equivalent conductances are computed by ThermalDesktop and output as conductors taking into account the entire network of Super Nodes. Unfortunately, this does have one drawback in that a connection is established between every Super Node. This results in far more couplings, many of which are negligibly small and could possibly be eliminated with a minimal impact on results.

IV. Technique Implementation

The PLUME thermal model is shown in Figure 3, with the radiation only network on the left and the conduction only network on the right. Some surfaces are removed for display purposes.

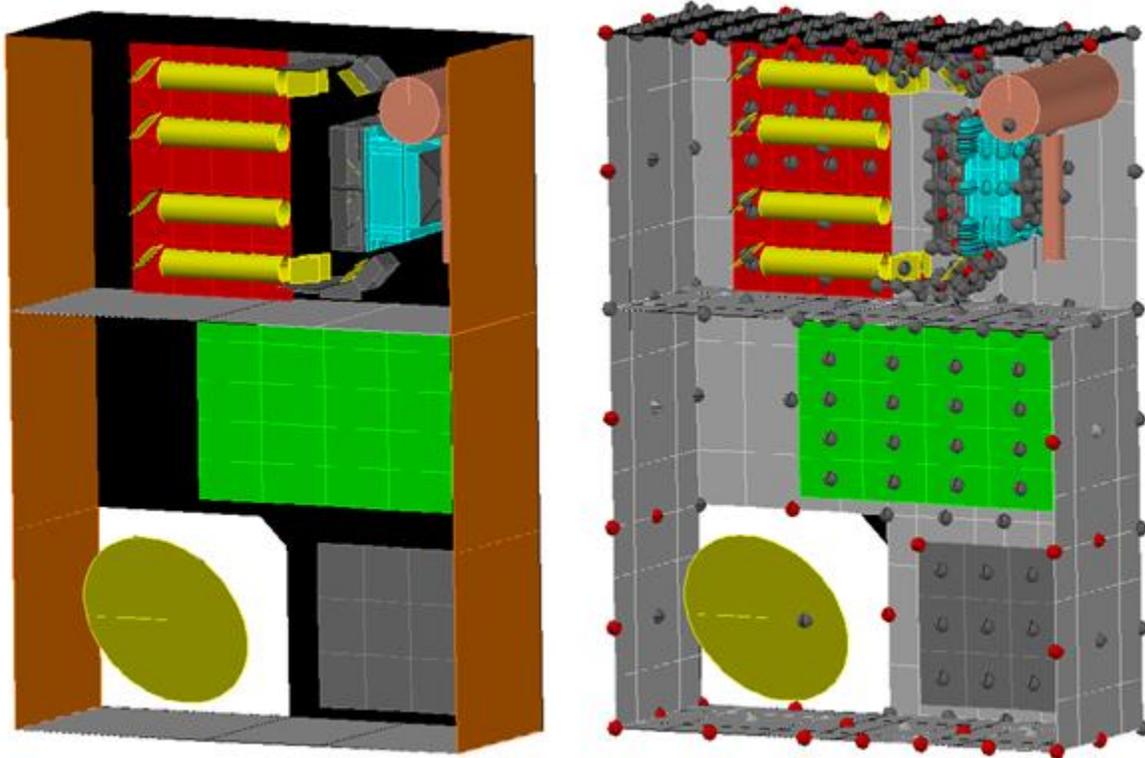


Figure 3 – PLUME Radiation Model (Left) and Conduction Model (right) – Back Panel removed for Clarity

The Hybrid approach was only used for surfaces which shared an edge with an adjacent surface. Other surfaces which did not share an edge, such as an electronics board or optical bench, were modeled with traditional centroid based surfaces for both radiation and internal conduction. Couplings from these surfaces to the chassis were made using conductors or contactors.

Comparing results between the edge node only approach and the Hybrid approach showed a marked improvement in computation time as shown in Table 1 for the Hybrid approach (approximately 4x faster). It should be noted that the largest performance improvement was seen in the Radiation Coupling computation, which is often the most computationally demanding portion. Additionally, cases were run using the Super Network feature and results proved identical to the Hybrid approach. Lastly, a case was run which removed the negligible Super Node couplings (defined as $<1E-5$ W/K for this run). Table 1 shows the differences in results for the various cases. The numbers of couplings and nodes are also included for comparison. For this model, three submodels employed the hybrid approach: ISOLATOR, PLUME, and OPT_SUP. The largest average DT was found for the BOARD submodel, which was modeled using traditional centroid based methods in all cases.

	Edge Node (Baseline)	Hybrid	Hybrid+ SuperNetwork	Hybrid+ SuperNetwork Filtered
Number of Radiative Nodes	1012	410	410	410
Number of TMM Nodes	1067	1067	531	531
Number of Radiative Couplings	65380	10646	10646	10646
Number of TMM Couplings	1993	1993	10013	5094
Time to Solve HeatRate [s]	118	72	72	72
Time to Solve Radiation Couplings [s]	624	90	90	90
Time to Solve TMM [s]	491	142	136	116
Max DT (Orb Avg – Orb Avg) [°C]		6.7		6.4
Avg DT (ISOLATOR) [°C]		-0.423		-0.08
Avg DT (PLUME) [°C]		0.403		0.11
Avg DT (OPT_SUP) [°C]		-0.078		0.015
Avg DT (BOARD) [°C]		1.35		1.35

Table 1 – Comparison of Hybrid Method to Edge Node Approach for PLUME Model

Overall, for a proposal level model, the error associated with the method is relatively small. Furthermore, it has identified regions of the model where one node may not be sufficient to accurately capture the heat flow. Two areas identified are the BOARD and ISOLATOR submodels. For the BOARD submodel, direct couplings from the BOARD to the PLUME chassis, which acts as the radiator, resulted in the discrepancy. For the Edge Node baseline case, this coupling went to an edge node that directly radiates to space; while in the Hybrid approach, the heat must further travel through the additional resistance to reach the centroid node to be rejected to space.

For the Max DT discrepancy, the specific node with the largest deviation is in the ISOLATOR submodel. The assumption that radiation is a minimal effect was incorrect for this particular node. The isolator is responsible for supporting a very cold detector and consequently results in a very large temperature delta with the surroundings. Therefore, radiation plays a more dominant role than in other areas of the model. The additional discretization of the isolator in the baseline edge node case provides for a more accurate representation of the heat exchange. This could be mitigated by including additional radiation nodalization for the affected regions in the ISOLATOR submodel.

V. Future Improvements

Additional developments could further refine or ease the use of this technique. Since only the surface edges need to be connected, the conduction only mesh could be reduced to only introduce new nodes at the edges. This would result in an $(n+2) \times (m+2)$ *Conduction Only Surface* for an $n \times m$ *Radiation Only Surface*. This may be accomplished by adding a very small delta (e.g. 0.0001) to the first edge node breakdown and $(1-\text{delta})$ to the last. So, a (0.25,0.5,0.75) centroid breakdown would become a (0.0001, 0.25,0.5,0.75,0.9999) edge node breakdown. For 1×1 surfaces, this approach results in the same number of additional nodes, but for subdivisions greater than 1×1 , it eliminates the internal conduction nodes.

Additional automated filtering could also be added to reduce the number of generated couplings as many of these are likely negligible in the overall energy balance. Reduction of these terms might need to further compensate for the loss of overall system conductance to reduce the inaccuracy of neglecting conduction terms from the energy balance. While the actual heat flow from Node A to Node F may go through nodes B, C, D, and E and be very small, the elimination of the direct coupling between A and F may need to increase the coupling from A to B, B to C, and elsewhere. As a first order approximation, the total conductance removed by eliminating small couplings could be compensated as follows for each coupling that remains:

$$G_{i-j,\text{remaining}} = G_{i-j,\text{remaining}} * \left\{ \frac{[\text{Sum}(G_{i,\text{remaining}}) + \text{Sum}(G_{i,\text{removed}})]}{\text{Sum}(G_{i,\text{remaining}})} \right\} \\ * \left\{ \frac{[\text{Sum}(G_{j,\text{remaining}}) + \text{Sum}(G_{j,\text{removed}})]}{\text{Sum}(G_{j,\text{remaining}})} \right\}$$

Non-subdividable surfaces, such as triangles and polygons, must currently be manually generated using Finite Elements, but so long as the proper connections are made at corners and along the edges, the approach works for these shapes as well. One further advantage with using Finite Elements, as opposed to edge nodes, is the ability to change the element shape simply by moving the nodes. This approach could also be extended to edge node surfaces

by converting them to Finite Elements, but then the ability to change the mesh density is lost, since the elements no longer have a connection to a surface.

It is also possible that a script could be developed and used to automate the entire process. Since no further user input to control the process flow is needed after defining the original surfaces, features could be added to ThermalDesktop to explicitly generate the surfaces, or implicitly generate the surfaces internally to create the thermal network.

VI. Conclusions

A new technique for thermal modeling that uses a hybrid Edge Node surface for conduction and a Centroid surface for radiation has been developed, implemented, and tested. The resulting model is readily able to be exported to other analysis codes that may not support the Edge Node feature of ThermalDesktop. It also offers advantages in reducing the time necessary to generate the conduction network by leveraging the capabilities of Edge Nodes in ThermalDesktop. Furthermore, it may reduce the run time for solving the radiation network by excluding the Edge Nodes from radiative calculations resulting in a smaller subset of surfaces for which radiation must be calculated. While the additional effort of maintaining two sets of surface may seem significant, the derivation of one set from the other is, in actuality, a minimal effort. The only identifiable drawback is the inclusion of either numerous additional nodes or numerous additional conduction couplings (if using the Super Network feature). However, elimination of these additional coupling may be performed and have a negligible impact on the resulting model predictions.

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