SPACE MANEUVER VEHICLE TEAM CONCEPT DESIGN CENTER THERMAL MODULE: A PARADIGM SHIFT[1]

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ABSTRACT

Five years ago, the Concept Design Center at The Aerospace Corporation was formed to provide a focus for Concurrent Engineering at the early stage of the design process. The initial focus was to develop a process for specialists from multiple disciplines to perform the conceptual design for a constellation of satellites. Several teams have been derived from the initial team to focus on specialized applications. One of these teams is focused on the Space Maneuver Vehicle[1], which is a reusable space vehicle, similar to the X-37[2] and the X-33. The team's purpose is to perform studies to estimate the cost of the Space Maneuver Vehicle for different sets of requirements.

All of the Concept Design Center teams have a component to estimate the Thermal Control Subsystem mass and power. A linear predictive model is employed within the Space Segment Team Thermal Module for this purpose. This model has limitations for estimating the mass and power when new technologies will be utilized. A new Thermal Module was developed for the Space Maneuver Vehicle Team using data from representative new technologies.

This module is a radical change from previous Thermal Modules. The new module sizes the radiator area and the heat transport capacity to meet the desired thermal performance based upon the algorithms used for spacecraft thermal analysis. The modeling approach for the new module applies the principles used for detailed thermal design. The Concept Design Center environment poses a unique challenge to the satellite design synthesis problem because one design iteration must be completed in less than one hour.

The advantage of the new Thermal Module is the increased fidelity of the modeling process and greater confidence in the estimated mass and power. Since the predicted thermal performance is based upon a methodology used for spacecraft thermal analysis, the output of the Thermal Module should be reproducible by a contractor when the same assumptions are made.

INTRODUCTION

Prior to the initiation of the first Space Maneuver Vehicle Team (SMVT) study in March 2000[1], a Thermal Module had been developed for two different Concept Design Center (CDC) Teams: the Space Segment Team (SST)[3] and the Electro-Optical Team (EOPT)[4]. Two different

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modeling approaches were taken for these modules, which estimate the mass and power required to meet the mission requirements.

The SST Thermal Module used a predictive model to estimate the Thermal Control Subsystem (TCS) mass and power for a spacecraft bus[3]. Since the TCS mass and power are a small part of the overall spacecraft mass and power, this assumption may be valid. This approach does not take into account the differences in the bus geometries or different bus technologies.

The EOPT Thermal Module estimated cryogenic cooling requirements to cool up to three infrared sensors with wavelengths in the Long Wavelength IR (LWIR), Medium Wavelength IR (MWIR) and Short Wavelength IR (SWIR) electromagnetic spectrum[4]. The module sized the cryocoolers and cryostats required to meet the cooling requirements.

Based upon the shortcomings of the existing two modules, a decision was made to build a new Thermal Module for the first SMVT CDC Study. The rationale for the development of a new module was the desire to assess the impact of the different vehicle configurations, which could not be done with either the EOPT or the SST Thermal Modules. The new module incorporates a thermal math model (TMM) to predict the vehicle temperatures. A finite difference equation solver was added to solve the governing equations in the TMM. The TMM requires the calculation of the radiation interchange factors and environmental flux incident upon the exterior SMV surfaces. For the SMVT001 Study, the radiation interchange factors and environmental fluxes for one vehicle geometry were used for all of the vehicle configurations studied. In this approach, the impact of vehicle configuration changes upon the thermal power and mass estimates could be assessed with some inherent error.

As a follow-on task to the SMVT001 Study, the module was upgraded to solve the shortcomings of the fixed vehicle geometry. The new module utilizes the information from the Vehicle Configuration Module to produce a representation of the revised vehicle geometry in the TMM. The changes in the vehicle geometry can now be incorporated into the thermal design process. An iteration of the thermal design cycle can be performed within the time constraints of the SMVT CDC session.

SMV THERMAL ANALYSIS

Spacecraft thermal design synthesis is a multi-step procedure whose objective is to ensure that the component temperatures do not exceed their allowable range. Component temperatures are predicted and compared to the allowable temperatures to determine if the design meets the requirements. This analysis process is very complex and must include the impact that the space environment has upon the spacecraft. Two models, a geometric math model (GMM) and a TMM, must be developed for this analysis.

The GMM contains a representation of the spacecraft's geometric surfaces, and is used to compute the radiation interchange factors between surfaces and external environmental fluxes. Several programs can perform these calculations. The most accurate method for determining the surface interactions utilizes a Monte Carlo Ray Tracing algorithm to determine the surface interactions. Turner Associates Consultants was the developer of the first Monte Carlo Ray Tracing algorithm program for spacecraft thermal analysis, NEVADA[5]. ATRIUM is a software tool developed at The Aerospace Corporation to compute radiation interchange factors and environmental fluxes. ATRIUM uses Monte Carlo Ray Tracing algorithms with some enhancements to reduce the run time.

The TMM incorporates the nodes, conductors, and internal and external heating of the spacecraft. A Finite Difference Equation solver is used to compute the temperature predictions for the TMM. A steady state solution or a transient solution can be found for the TMM.

SINDA/G[6] is a commercial product that was first developed in the 1960s to produce temperature predictions for a TMM. A similar capability to predict temperatures using Microsoft Excel has been developed by Ray Garcia of Jet Propulsion Laboratory (JPL). This capability has been enhanced by reducing the run time to 2 minutes for a 30 node thermal model.

Figure 1 represents the Spacecraft Thermal Design Synthesis process applied to the SMVT CDC. Prior to the start of a SMVT CDC session, the surfaces comprising the GMM are defined in a Microsoft Excel worksheet. The worksheet computes the geometric dimensions of the surfaces and maintains the geometric relationships between the surfaces. The GMM file is generated by Microsoft® Visual Basic For Applications® (VBA) macros and is transferred to a Sun® Workstation where ATRIUM is run.

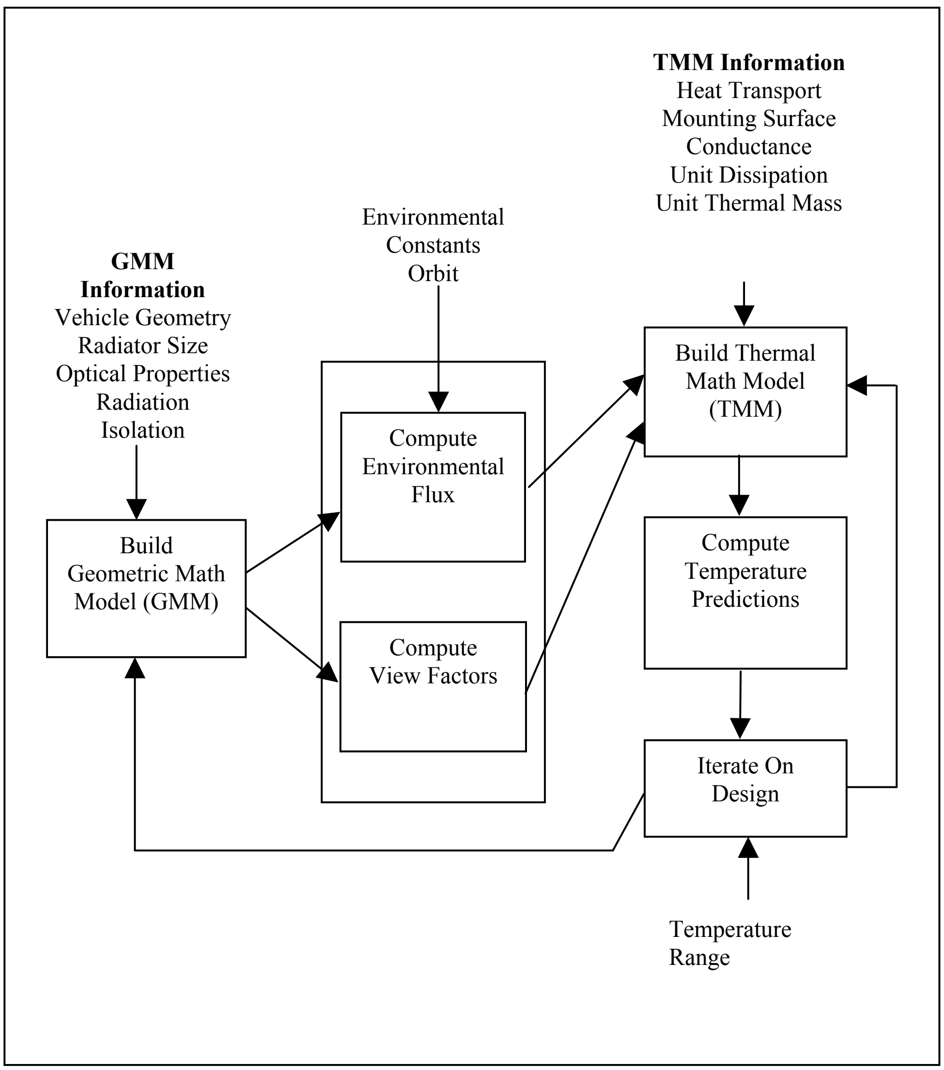

Figure 1 Spacecraft Thermal Analysis Process

Two types of ATRIUM runs are made: a view factor run and an environmental run. The two outputs from ATRIUM are the radiation interchange factors and environmental fluxes. The two output files are transferred to a PC and imported into the SMVT CDC Thermal Module. Both of the ATRIUM outputs are used by the TMM. The environmental fluxes represent the solar and planetary heating of the TMM nodes, and the radiation interchange factors represent the nodal radiation conductors. A Finite Difference Equation solver computes the temperature prediction for each node. The last step in this process is the comparison of the temperature predictions with the allowable temperature range.

If the temperature predictions exceed the allowable temperature range, some aspect of the design must be modified and the process must be repeated. The two options available are to modify the GMM or the TMM. Table 1 presents the information required to support this process and its source.

Table 1 SMV Thermal Module Information Source

Type of Information	Details	Source
Vehicle Geometry	Vehicle Dimensions Dimension Constraints	CDC Vehicle Configuration Module SMV CDC Vehicle Configuration
Radiator Size		Computed During CDC Session
Optical Properties	Thermal Protection System Properties Radiator Properties	NASA TPSX Database Satellite Thermal Control Handbook[7]
Radiation Isolation	MLI Location	SMV CDC Vehicle Configuration
Heat Transport Characteristics	Loop Heat Pipe capacity and unit mass	Informal Discussions - Thermal Control Technology Workshop
Mounting Surface Conductance	Mounted, Bolted and Heat Pipe Interfaces	Satellite Thermal Control Handbook[7]
Unit Dissipation	Unit Dissipation by Mode	CDC Power, CD&H, TT&C Module
Unit Thermal Mass	Power, CD&H, TT&C Mass	CDC Power, CD&H, TT&C Module
Thermophysical Properties	Specific Heat	Spacecraft Thermal Department's Thermophysical Properties Database

SMV THERMAL MODULE STRUCTURE

The capability to analyze multiple operating cases is a requirement for thermal analysis, e.g., the hot operating case and cold non-operating case. The radiator size is determined in the hot case and the heater size is determined in the cold non-operating case. Both of these cases require environmental fluxes for analysis. A significant source of the environmental flux is the sun. The solar absorptance of the radiator surfaces is degraded in the space environment. The solar absorptance degradation for commonly used radiator surface optical finishes is available from laboratory tests and flight measurements[7]. The End-Of-Life (EOL) and the Beginning-Of-Life (BOL) solar absorptances are used to compute the hot case and the cold case environmental fluxes, respectively.

The capability to analyze multiple design cases is an important feature of the SMV CDC Thermal Module. This capability has been implemented by using a naming convention for worksheets in the SMVT CDC Thermal Module and Microsoft Visual Basic For Applications (VBA) macros that recognize the naming convention.

The purpose of the GMM and the TMM was described in the previous section. Generally speaking, the naming convention used for the worksheets containing the GMM and the TMM has a prefix followed by a unique identifier. Geometric information is contained in a worksheet with a prefix of GMM. Orbital information used to compute environmental flux has a prefix of ORB. The nodes, conductors and the information used to compute the temperature predictions are contained in worksheets that have a prefix of TMM. Environmental fluxes used in the TMM calculations will have the same unique identifier as the TMM worksheet and a prefix of EnvtFlux. The transient solution output for a TMM will be stored on a separate worksheet with a prefix of TRS.

The SMV CDC Thermal Module consists of three worksheets used to summarize the thermal analysis results and communicate with other SMV CDC users. These worksheets are named INPUT, OUTPUT and SUMMARY. The INPUT and OUTPUT worksheets follow the standard naming convention used by the CDC for module communications. Using the naming conventions of the SMVT CDC Thermal Module, multiple GMMs can exist in the module with each containing a different GMM vehicle geometry. An example of the use of this feature occurred during the second SMV CDC Session[7]. Two different types of solar arrays needed to be analyzed and the two GMMs were stored on separate GMM worksheets.

Combo Boxes, a graphical control used within a Microsoft Windows application, controls the GMM case, the orbital case, and the TMM case for the current CDC configuration. The Combo Boxes are updated when the thermal module worksheet is first opened and whenever a change is made to the workbook structure.

The functions required to execute the thermal analysis functions are initiated by selecting menu items on Tools Menu. The menu items and their purpose are described in Table 2.

Table 2 SMV CDC Thermal Module Tools Menu Items

Tools Menu Items	Worksheet Types Affected	Description
Thermal Update	Inputs	Retrieve CDC Module Outputs
Clone Sheet	GMM, ORB, TMM	Duplicate the selected worksheet with a different name
Rebuild TMM Model	Summary, TMM	Extract the Node and Conductor information from the Summary worksheet and rebuild the TMM worksheet
Create VF File	GMM	Generate the GMM File for the ATRIUM View Factor run
Create Sel Env File	GMM, ORB	Generate the GMM File for the ATRIUM Environmental Run
Run SS Selected	TMM	Compute steady state temperature predictions for the TMM Case
Run Transient Selected	TMM	Compute the transient temperature predictions for the TMM Case
Update Radiator Height	TMM, GMM, Summary	Update the changes made to the TMM radiator height to the GMM Case
Update Fluxes	TMM	Import the ATRIUM environmental flux outputs into the TMM Case
Update RADKs	TMM	Import the ATRIUM View Factor outputs into the TMM Case

CONCLUSIONS

A new Thermal Module has been developed for the SMVT CDC. This new module implements thermal analysis techniques within Microsoft Excel. The Aerospace Corporation's in-house developed software code for Monte Carlo Ray Tracing algorithm, ATRIUM, complements the module by computing the radiation interchange factors and environmental fluxes. An efficient means of producing the GMM and importing the radiation interchange factors and environmental fluxes has been developed. A Finite Difference Equation Solver, originally developed by Ray Garcia of JPL, has been modified and incorporated into the module. Typical run times are less than 2 minutes for a 30 node thermal model. A CDC session design iteration can be performed within a 20-minute time period. Prior to the start of the CDC Session, a geometric model of the SMV's external surfaces is developed which can be scaled to the dimensions defined by the Vehicle Configuration CDC Module.

The methodology and software developed for the SMVT CDC Session is directly applicable to other CDC Teams. In addition, this approach can also be used to provide a timely way to compute temperature predictions for launch support and Source Selection evaluations.

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NOMENCLATURE, ACRONYMS, ABBREVIATIONS

ATRIUM	Aerospace Thermal Radiation Interchange Using Monte-Carlo
CDC	Concept Design Center
EOPT	Electro-Optical Team
GMM	Geometric Math Model
LWIR	Long Wavelength IR
MWIR	Medium Wavelength IR
NEVADA	Net Energy Verification and Determination Analyzer
SMV	Space Maneuver Vehicle
SMVT	Space Maneuver Vehicle Team
SST	Space Segment Team
SWIR	Short Wavelength IR
TCS	Thermal Control System
TMM	Thermal Math Model