Thermal Systems Analysis Toolbox (TSAT) Quickstart Guide

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The Thermal Systems Analysis Toolbox (TSAT) is a MATLAB/Simulink based toolbox for the modeling and analysis of dynamic and steady-state thermal system. This document serves as a quickstart guide to get new users up and running fast. The guide includes an introduction with general information about TSAT, discusses installation, describes the Simulink library and MATLAB tools, and provides direction to using TSAT.

I. Introduction

THE Thermal Systems Analysis Toolbox (TSAT) is a MATLAB/Simulink ® based tool for modeling and analysis of thermal systems. It was created during the development of thermal models of aero-engines for the purpose of approximating the thermal environment relevant for control system components when considering the application of distributed engine control. Also of interest was thermal modeling relevant to high pressure turbine tip clearance control. A significant portion of the Simulink blocks and MATLAB functions provided in this software package were a direct result of these research efforts. Other blocks and functions have been added to widen TSATs applicability and help to make it a well-rounded toolset for thermal system modeling.

TSAT provides a modular block-diagram environment for modeling and analyzing dynamic thermal systems. It is conducive to system modeling and control design efforts involving consideration of the physics of thermal systems. The toolbox consists of a number of Simulink blocks and MATLAB functions that can be used in combination with each other and MATLAB/Simulink's built-in tools to model and analyze thermal systems.

TSAT is mainly concerned with modeling heat transfer, particularly with structures that can be modeled using a 1-D or 2-D approach. This applies to planar and cylindrical geometries. Although the tools of TSAT could be used more generally, its tools were created primarily to support this task. The 1-D and 2-D transient conduction modeling blocks are at the core TSAT while the rest of the blocks and functions are meant to support these blocks through aiding in supplying boundary conditions, and or performing a general-use functions that facilitate the modeling of heat transfer involving a solid structure.

TSAT was developed to be a modular modeling environment. The Simulink environment allows blocks representing various objects, fluids, boundary conditions, etc. to be dropped into a block diagram and linked together. This can provide an intuitive and simplified method for modeling thermal systems, particularly when considering dynamics. TSAT takes advantage of Simulink's block diagram modeling environment, making it conducive to these types of modeling applications. A powerful feature of TSAT is its modular nature that allows a complex problem to be broken into smaller problems. For instance, a larger and more complex structure could be broken into various parts and linked together through boundary conditions to model the overall structure. This is possible with TSAT, thus allowing relatively simple tools to be used to model complex problems. At the same time, computational efficiency could be improved.

The rest of this document is organized as follows: Instructions are provided on how to install and un-install TSAT, the Simulink Library tools are discussed, the MATLAB tools are discussed, and publications that illustrated TSATs utility are listed. For further help with TSAT, refer to the provided examples, the help files of the Simulink blocks, and the comments within the MATLAB function files.

II. Install and Un-install

To install TSAT execute the following steps:

1. Download TSAT from the GIT server PUT URL HERE, click the green download button for the latest version, and extract the files to a folder that can be accessed by MATLAB, ensuring there are no spaces in the path name. Note that TSAT was developed in a Windows 7 environment using MATLAB R2015a. It is not guaranteed to work on other operating system or with different versions of MATLAB/Simulink.

2. Open up MATLAB and navigate to the directory that TSAT was saved.
3. Run *install_TSAT.m*. This will setup the paths for TSAT. A temporary install should only save the paths for the current MATLAB session while the permanent install option will save the paths to MATLAB until the uninstall script is ran or the paths are manually removed. If the user does not have elevated privileges, the paths may not be saved properly. If the paths have not been saved, new paths must be manually added to the *pathdef.m* file. To do this click on the "Set Path" icon in the MATLAB toolbar and add the following paths by navigating to them and selecting them:
    - Trunk\TSAT_Library
    - Trunk\TSAT_Library\TSAT_Support
    - Trunk\TSAT_Tools
    - Trunk\TSAT_Tools\Tools
    - Trunk\TSAT_Library\MATLAB_Scripts

   Save the paths before exiting the dialog box.
4. Open up Simulink and verify that the TSAT library shows up in the library browser.
5. Open up one of the examples in the "TSAT\Trunk\TSAT_Examples" folder and attempt to execute it to verify that the TSAT library is on the path and the library blocks can be used.

To un-install TSAT execute the following steps:
1. Run *uninstall_TSAT.m*. This will remove the paths that were added during the TSAT install.
    a. If the paths were added manually during installation then they must be removed manually using the "Set Path" tool in MATLAB.

III. Simulink Library

The TSAT library is accessible from the Simulink library browser which is linked to *TSAT_Lib.slx*. This file is linked to 7 sub-libraries:
1. *TSAT_AirProps.slx* – contains several blocks used to approximate thermal properties of air including heat capacity, specific heat at constant volume, dynamic viscosity, and thermal conductivity.
2. *TSAT_Conduction.slx* – contains blocks to perform 1-D and 2-D heat conduction with the ability to consider conduction, convection, and radiation boundary conductions.
3. *TSAT_Convection.slx* – contains various blocks useful in facilitating convective heat transfer parameters including Nusselt number and convective heat transfer coefficients for natural and forced convection. Also available are some tools for modeling fluid heat transfer, boundary layer modeling, calculating fluid properties, calculating non-dimensional quantities, and various other tools to support the other blocks in the library.
4. *TSAT_Deformation.slx* – contains blocks to model deformation of a structure due to thermal expansion/contraction. Currently this library only has one block for 1-D elastic thermal expansion but additional blocks could be added in the future.
5. *TSAT_GenHeatX.slx* – contains general heat transfer blocks. Currently the library only has one block which models a lumped mass heat transfer problem. In the future, additional blocks could be added.
6. *TSAT_GenTools.slx* – contains several general-use blocks that include functionality such as interpolation, polynomial fitting, matrix manipulation, averaging, and more.
7. *TSAT_Radiation.slx* – contains blocks to approximate radiation heat transfer coefficients for use in radiation boundary conditions of the 1-D and 2-D conduction blocks.

Each of the blocks within these libraries are saved as their own library file. All libraries reside in the "Trunk\TSAT_Library" folder. Each block has a help file that can be viewed by right clicking the block and left clicking "help". The help files are stored in the "Trunk\TSAT_Library\TSAT_Support" folder. Examples of how to use various TSAT blocks is demonstrated through several examples in the "Trunk\TSAT_Examples" folder. It is recommended that the user review several of the examples before attempting to build their own models.

The *TSAT_Conduction.slx* library is at the core of TSAT. The 2-D conduction blocks in this library can model planar or cylindrical structures, and can handle non-isotropic structures with material transitions and dynamically changing material properties. The conduction blocks employ finite difference method techniques but are efficient enough to model fairly complex problems without enormous computational times. The *TSAT_GenHeatX.slx* library is meant for more simplistic and general heat transfer modeling tools such as lumped mass modeling. The remaining libraries are mostly meant to supplement these 2 libraries but facilitating the generation of boundary conditions. The following table lists each block in the TSAT library. For more information the user is referred to the help menu for each block and the examples provided in the “Trunk\TSAT_Examples” folder.

Library	**Block**
TSAT_AirProps.slx	Air Properties – Heat Capacity
TSAT_AirProps.slx	Air Properties – Specific Heat at Constant Volume
TSAT_AirProps.slx	Air Properties – Thermal Conductivity
TSAT_AirProps.slx	Air Properties – Viscosity [mu] (slug/ft-sec)
TSAT_Conduction.slx	1D Trans Conduction model – variable props & general BCs
TSAT_Conduction.slx	1D Trans Conduction model – variable props & general BCs (Iterative Subsystem Capable)
TSAT_Conduction.slx	2D Transient Conduction Model – ADI Crank-Nicolson
TSAT_Conduction.slx	2D Transient Conduction Model – ADI Crank-Nicolson (Iterative Subsystem Capable)
TSAT_Conduction.slx	Interface Temperature
TSAT_Conduction.slx	2D Transient Conduction Model – Fully Implicit
TSAT_Conduction.slx	2D Transient Conduction Model – Fully Implicit (Iterative Subsystem Capable)
TSAT_Convection.slx	Forced Convection: Laminar Internal Flow for Various Shapes
TSAT_Convection.slx	Forced Convection: Laminar Circular Tube Annulus
TSAT_Convection.slx	Force Convection: Laminar Coiled Tube
TSAT_Convection.slx	Simple Convective Heat Transfer
TSAT_Convection.slx	Forced Convection - Dittus Boelter
TSAT_Convection.slx	Forced Convection - Sieder-Tate
TSAT_Convection.slx	Forced Convection - Gnielinski
TSAT_Convection.slx	Forced Convection - Laminar Flat Plate
TSAT_Convection.slx	Force Convection - Laminar Flat Plate - Churchill Ozoe
TSAT_Convection.slx	Flat Plate Incompressible Laminar Boundary Layer (Zero PG)
TSAT_Convection.slx	Falkner-Skan (Tw - Te = Constant)
TSAT_Convection.slx	Falkner-Skan (Tw - Te = Polynomial)
TSAT_Convection.slx	Forced Convection - Turbulent Flat Plate
TSAT_Convection.slx	Flat Plate Incompressible Turbulent Boundary Layer (Zero PG)
TSAT_Convection.slx	Turbulent Flat Plate 1/7 Power Law (Tw-Te = Polynomial)
TSAT_Convection.slx	Turbulent Convection on Axisymmetric Body w/ Varying Velocity and Temperature
TSAT_Convection.slx	Forced Convection - Mixed BL Flat Plate
TSAT_Convection.slx	Flat Plate Incompressible Mixed Boundary Layer (Zero PG)
TSAT_Convection.slx	Forced Convection - Cylinder Cross Flow - Hilpert
TSAT_Convection.slx	Forced Convection - Square Rod Cross Flow - Hilpert
TSAT_Convection.slx	Forced Convection: Hexagonal Rod Cross Flow - Hilpert
TSAT_Convection.slx	Forced Convection: Thin Plate Cross Flow - Hilpert
TSAT_Convection.slx	Forced Convection: Cylinder Cross Flow - Zukauskas
TSAT_Convection.slx	Forced Convection: Cylinder Cross Flow - Churchill Bernstein
TSAT_Convection.slx	Forced Convection - Sphere Cross Flow - Whitaker
TSAT_Convection.slx	Forced Convection: Tube Bank - Zukauskas
TSAT_Convection.slx	Forced Convection: Impinging Jet
TSAT_Convection.slx	Free Convection - Vertical Plate Laminar Convection - Analytical
TSAT_Convection.slx	Free Convection - Vertical Plate/Cylinder or Inclined Plate
TSAT_Convection.slx	Free Convection - Horizontal Plate
TSAT_Convection.slx	Free Convection - Horizontal Cylinder
TSAT_Convection.slx	Free Convection - Sphere
TSAT_Convection.slx	Free Convection - Horizontal Rectangular Cavity (Heated Bottom)
TSAT_Convection.slx	Free Convection - Vertical Rectangular Cavity
TSAT_Convection.slx	Free Convection - Tilted Rectangular Cavity
TSAT_Convection.slx	Free Convection - Concentric Cylinders
TSAT_Convection.slx	Free Convection - Concentric Spheres
TSAT_Convection.slx	Simple Natural Convective Heat Transfer

TSAT_Convection.slx	Simple Natural Convective Heat Transfer II
TSAT_Convection.slx	Combined Forced & Natural Convection
TSAT_Convection.slx	Non-Dimensional Parameters
TSAT_Convection.slx	Hydraulic Diameter
TSAT_Convection.slx	Film Cooling Reference Temperature
TSAT_Convection.slx	Colebrook Correlation
TSAT_Convection.slx	Sutherland's Law
TSAT_Convection.slx	Ideal Gas Heat Capacity
TSAT_Convection.slx	Fluid Energy Balance
TSAT_Deformation.slx	Thermal Expansion 1D Elastic
TSAT_GenHeatX.slx	Lumped Mass Heat Transfer
TSAT_GenTools.slx	1D Linear Interpolation
TSAT_GenTools.slx	2D Linear Interpolation
TSAT_GenTools.slx	3D Linear Interpolation
TSAT_GenTools.slx	Averaging
TSAT_GenTools.slx	Weighted Averaging
TSAT_GenTools.slx	Matrix MinMax
TSAT_GenTools.slx	Polynomial Fit
TSAT_GenTools.slx	Sub-Matrix (2D)
TSAT_GenTools.slx	Logistic Function
TSAT_Radiation.slx	Radiation HeatX Coefficient – Non-Reflective Sink
TSAT_Radiation.slx	Radiation HeatX Coefficient – Reflective Planar Surfaces
TSAT_Radiation.slx	Radiation HeatX Coefficient – Reflective Concentric Cylinders

IV. MATLAB Tools

The MATLAB tools consist of several MATLAB functions. The MATLAB functions should be on the MATLAB path and therefore should be able to be used in any MATLAB script, function, or the MATLAB command window. The MATLAB functions can serve several purposes, mostly for general utility. Below is a list of the MATLAB functions provided with TSAT that are meant for use by the user.

- *CubicSpline.m*: returns the coefficients of all the cubic splines connecting points in a given data set.
- *CubicSplineInterp.m*: uses the cubic spline coefficient produced by "CubicSpline.m" to interpolate or return the first, second, or third derivative at any x-value(s) along the span of the original data set.
- *digitizeImage.m*: an interactive function that can be used to extract data from images.
- *extendLine.m*: this function will append a data set with an additional point to extend a line to the prescribed value through linear or cubic spline extrapolation.
- *lineOffset.m*: this function will offset a line above, below, or in both directions.
- *ReduceDataSet.m*: reduces a data set to be more consistent with the prescribed interval of the independent variable. For example, if time-dependent data is recorded at a rate that is much faster than is necessary for your application, this function can be used to reduce the data set to a more appropriate time interval.
- *ThermExp1DElastic.m*: Models 1D elastic thermal expansion of an object.
- *trimLine.m*: this function will truncate and append a data set with an additional point to trim a line to the prescribed value.
- *PolyProd.m*: given the coefficient of 2 polynomials, it returns the coefficients of the product of the 2 polynomials.
- *PolySum.m*: given the coefficient of 2 polynomials, it returns the coefficients of the sum of the 2 polynomials.

For more information the user is referred to comments within the functions (found in the examples in “Trunk\TSAT_Tools\Tools”) and the examples provided in “Trunk\TSAT_Tools\Examples”.

V. Publications

This section simply contains a list of publications that utilize TSAT or its concepts. The publications can be found through an internet search. These papers can serve as an example of how TSAT can be utilized to model and analyze thermal systems.

[1] Chapman, J., Kratz, J., Guo, T.H., and Litt, J., "Integrated Turbine Tip Clearance and Gas Turbine Engine Simulation," *Proceedings of the 52nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Salt Lake City, UT, 2016.

[2] Kratz, J., Culley, D., Chapman, J., "Approximation of Engine Casing Temperature Constraints of Casing Mounted Electronics," *Proceedings of the 52nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Salt Lake City, UT, 2016.

[3] Kratz, J., Chapman, J., and Guo, T.H., "A Parametric Study of Actuator Requirements for Active Turbine Tip Clearance Control of a Modern High Bypass Turbofan Engine," *Proceedings of the 2017 ASME Turbo Expo*, Charlotte, NC, 2017.

[4] Kratz, J., and Chapman, J., "Active Turbine Tip Clearance Control Trade Space Analysis of an Advanced Geared Turbofan Engine," *Proceedings of the 54nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Cincinnati, OH, 2018. To be published.

[5] Kratz, J., Culley, D., and Thomas, G., "Thermal Modeling of an Advanced Geared Turbofan for Distributed Engine Control Application," *Proceedings of the 54nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Cincinnati, OH, 2018. To be published.