Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)

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Outline

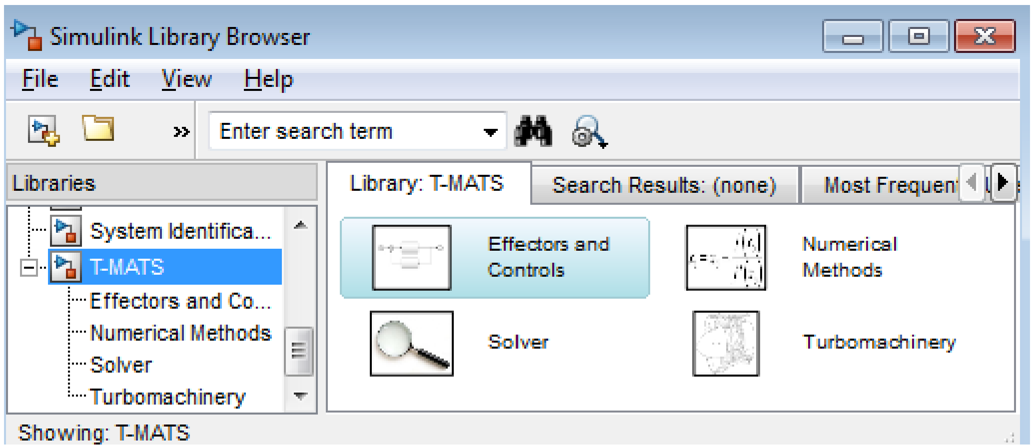
- T-MATS Description
- Framework
- Block Sets
- Examples
- Updates
- Recognition
- Summary
- Future work

T-MATS Description

- Toolbox for the Modeling and Analysis of Thermodynamic systems, T-MATS
  - Modular thermodynamic modeling framework
  - Designed for easy creation of custom Component Level Models (CLM)
  - Built in MATLAB®/Simulink®
- Package highlights
  - General thermodynamic simulation design framework
  - Variable input system solvers
  - Advanced turbo-machinery block sets
  - Control system block sets
- Development being led by NASA Glenn Research Center
  - Non-proprietary, free of export restrictions, and open source
    - Open collaboration environment

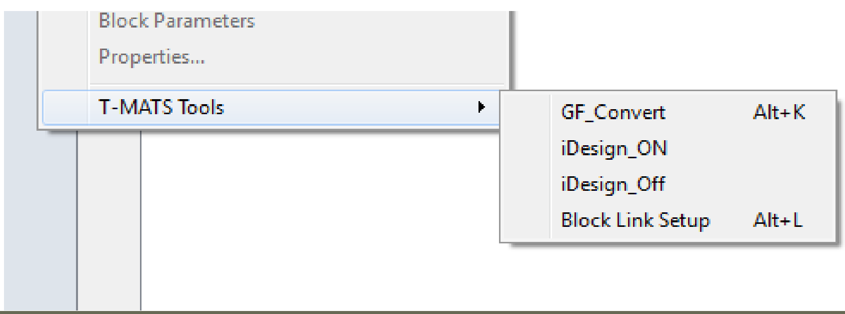
T-MATS Framework

- Plug-in for the industry-standard MATLAB/Simulink platform
  - additional blocks in the Simulink Library Browser:



Added Simulink Thermodynamic modeling and numerical solving functionality

  - additional diagram tools for model development in Simulink:

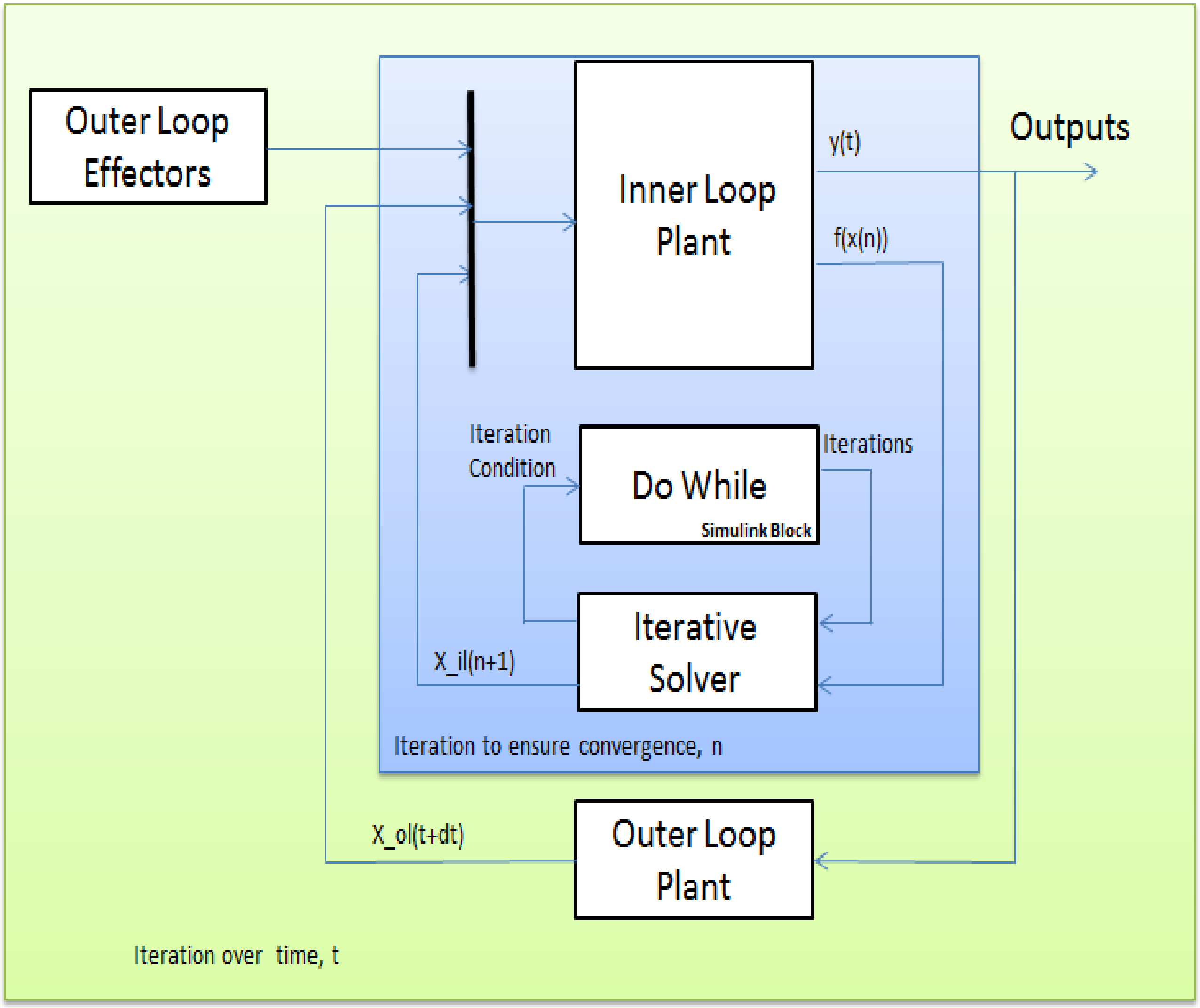


Faster and easier model creation

T-MATS Framework

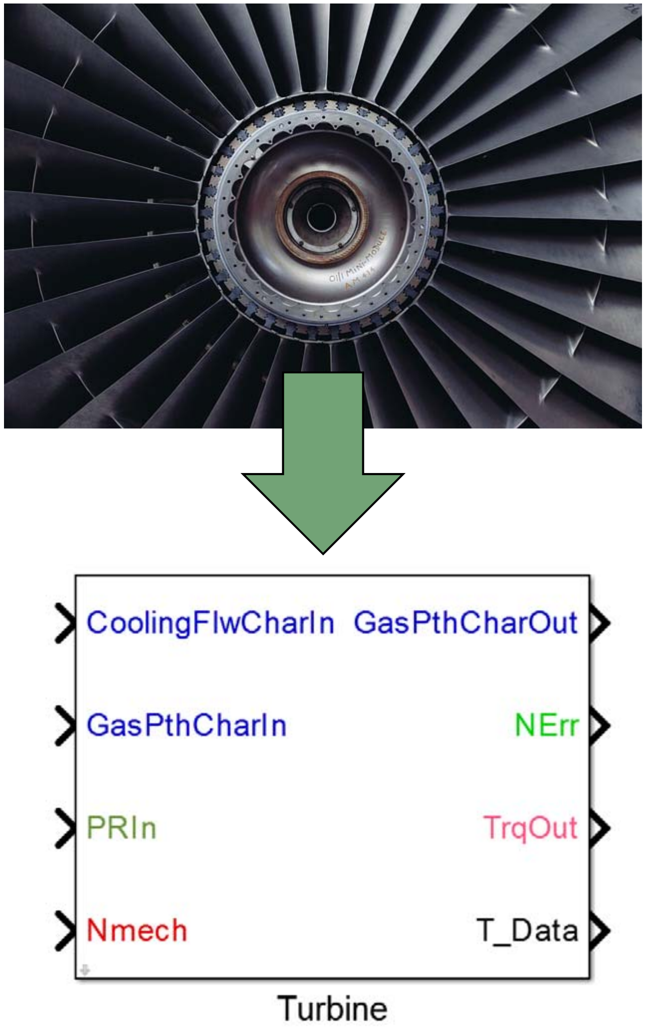
Dynamic Simulation Example:

- Multi-loop structure
  - The “outer” loop (green) iterates in the time domain
    - Not required for steady-state models
  - The “inner” loop (blue) solves for plant convergence during each time step



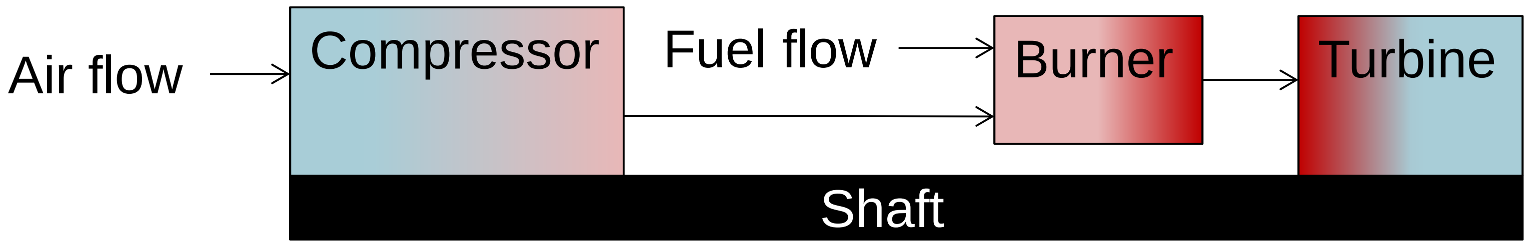
Blocks: Turbo-machinery

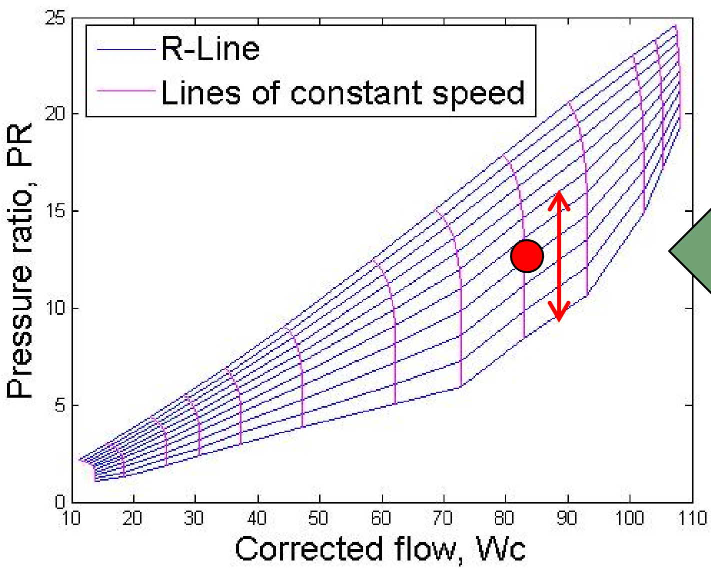
- T-MATS contains component blocks necessary for creation of turbo-machinery systems
  - Modeling theory based on common industry practices
    - Energy balance modeling approach
    - Compressor models utilize R-line compressor maps
    - Turbine models utilize Pressure Ratio turbine maps
  - Blocks types; compressor, turbine, nozzle, flow splitter, and valves among others.
    - Color Coding for easy setup
  - Built with S-functions, utilizing compiled C code/ MEX functions



Blocks: Numerical Solver

- T-MATS contains libraries of solvers based on the Newton Raphson method to ensure system convergence.
- Why is an external solver necessary?
  - In gas turbines, air flow through the engine is dependent on system architecture and a solver is required to achieve a balanced flow.

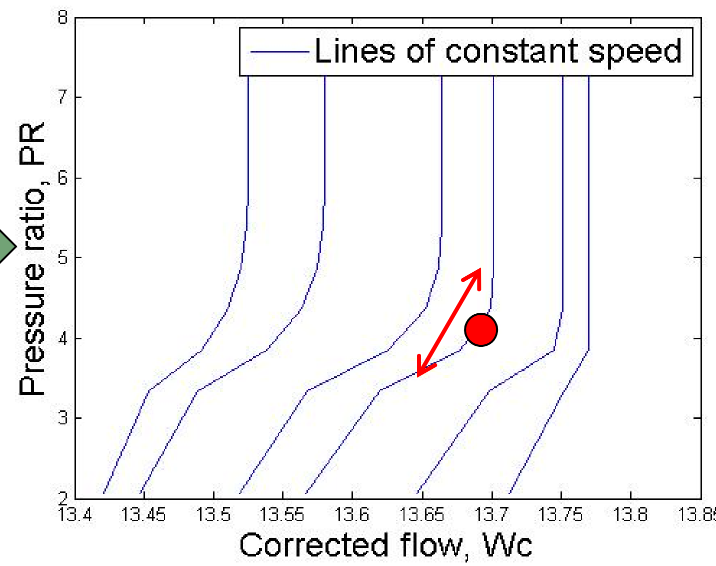




Components must agree on W for the system

Convergence

Effectors:
Shaft speed
Pressure
Temperature



Blocks: Controls

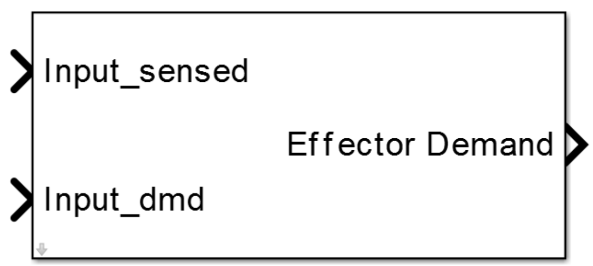
- T-MATS contains component blocks designed for fast control system creation
  - Sensors:

1st order Sensor

  - Actuators:

1st order Actuator

  - PI controllers:



Simple PI controller

Blocks: Settings

- The T-MATS Simulation System is a highly tunable and flexible framework for Thermodynamic modeling.

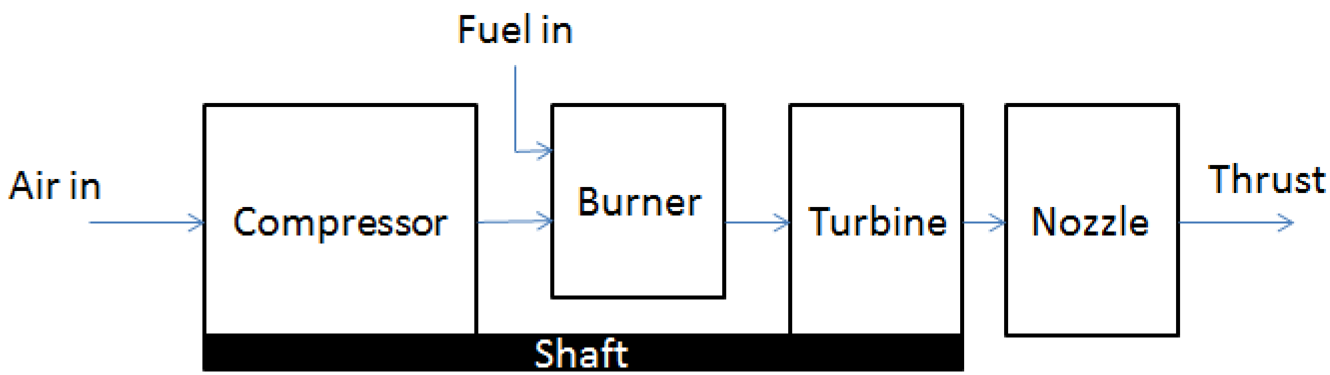
– T-MATS block Function Block Parameters
  - fast table and variable updates

– Open source code
  - flexibility in component composition, as equations can be updated to meet system design

– MATLAB/Simulink development environment
  - user-friendly, powerful, and versatile operation platform for model design

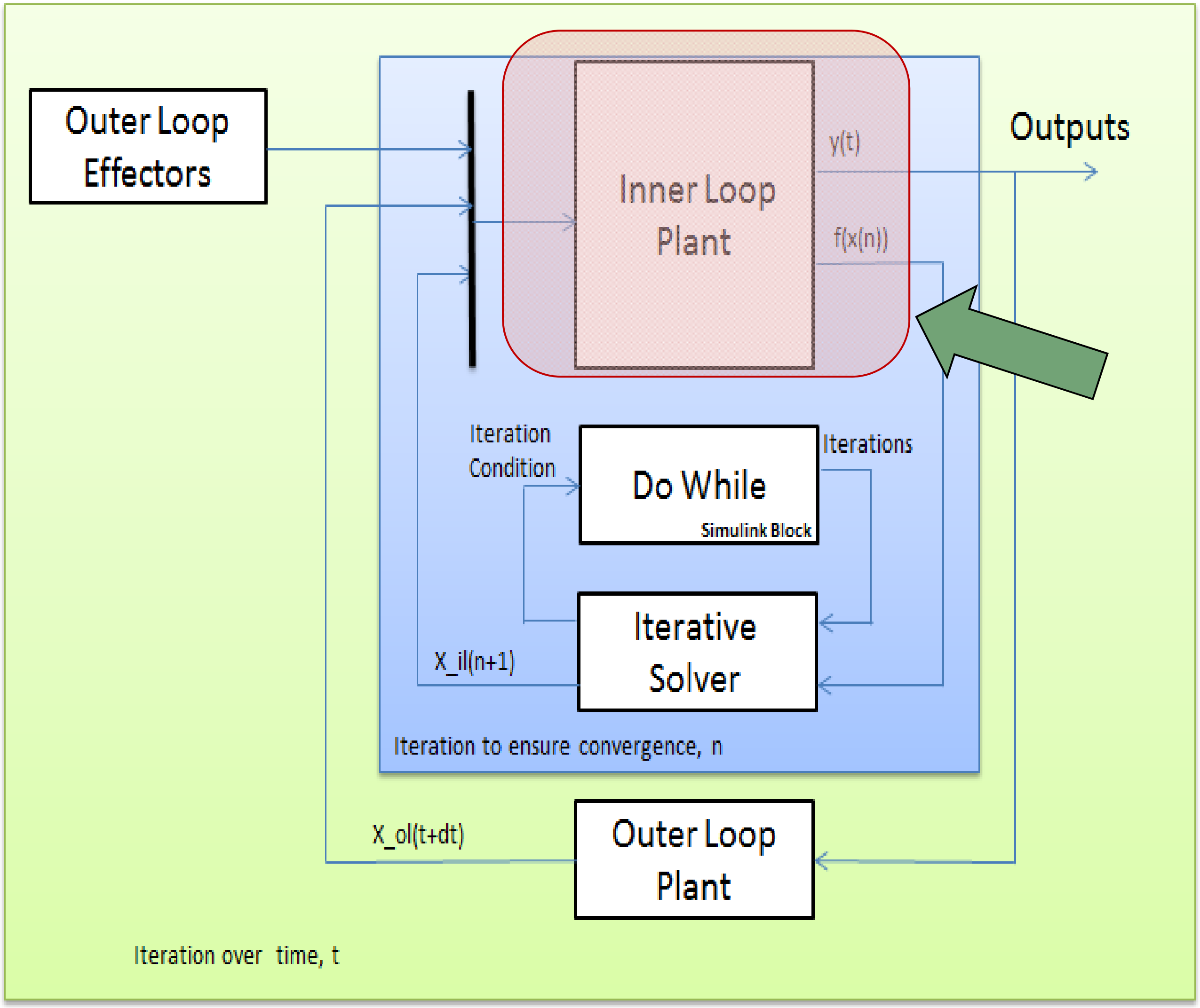
https://commons.wikimedia.org/wiki/File:Boeing%27s_commercial_aircraft_in_BBJ_livery.jpg

Dynamic Gas Turbine Example: Objective System

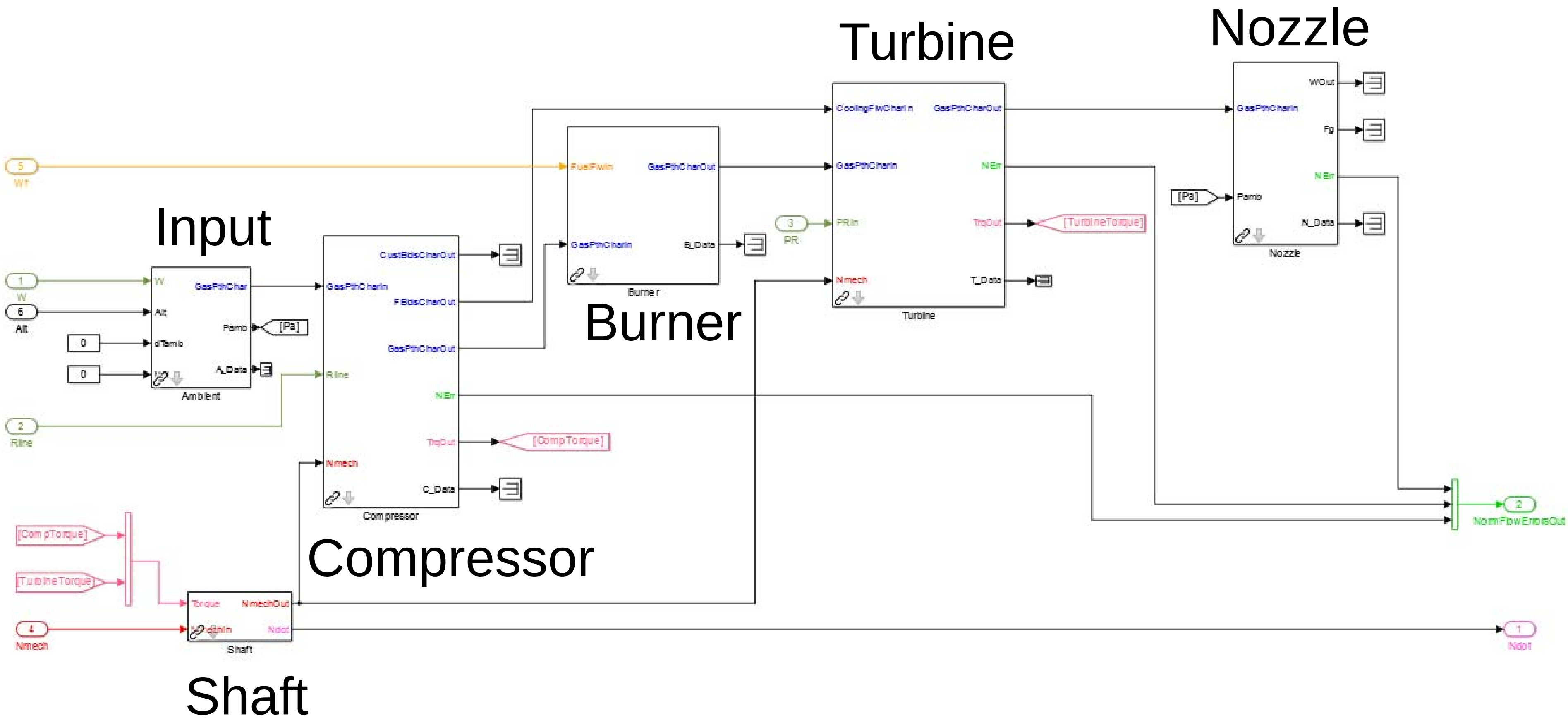


Simple Turbojet

Dynamic Gas Turbine Example: Creating the Inner Loop

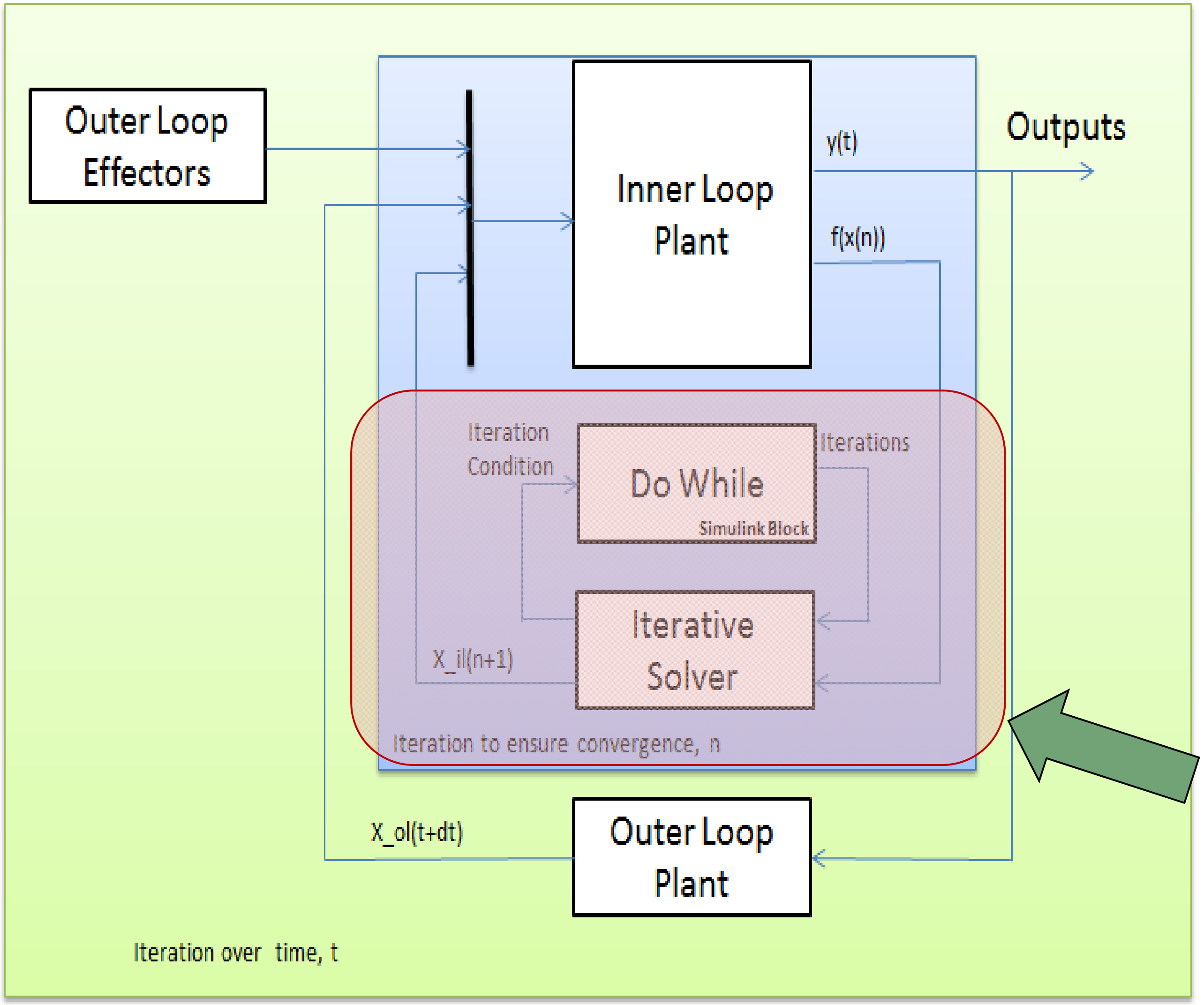


Dynamic Gas Turbine Example: Inner Loop Plant

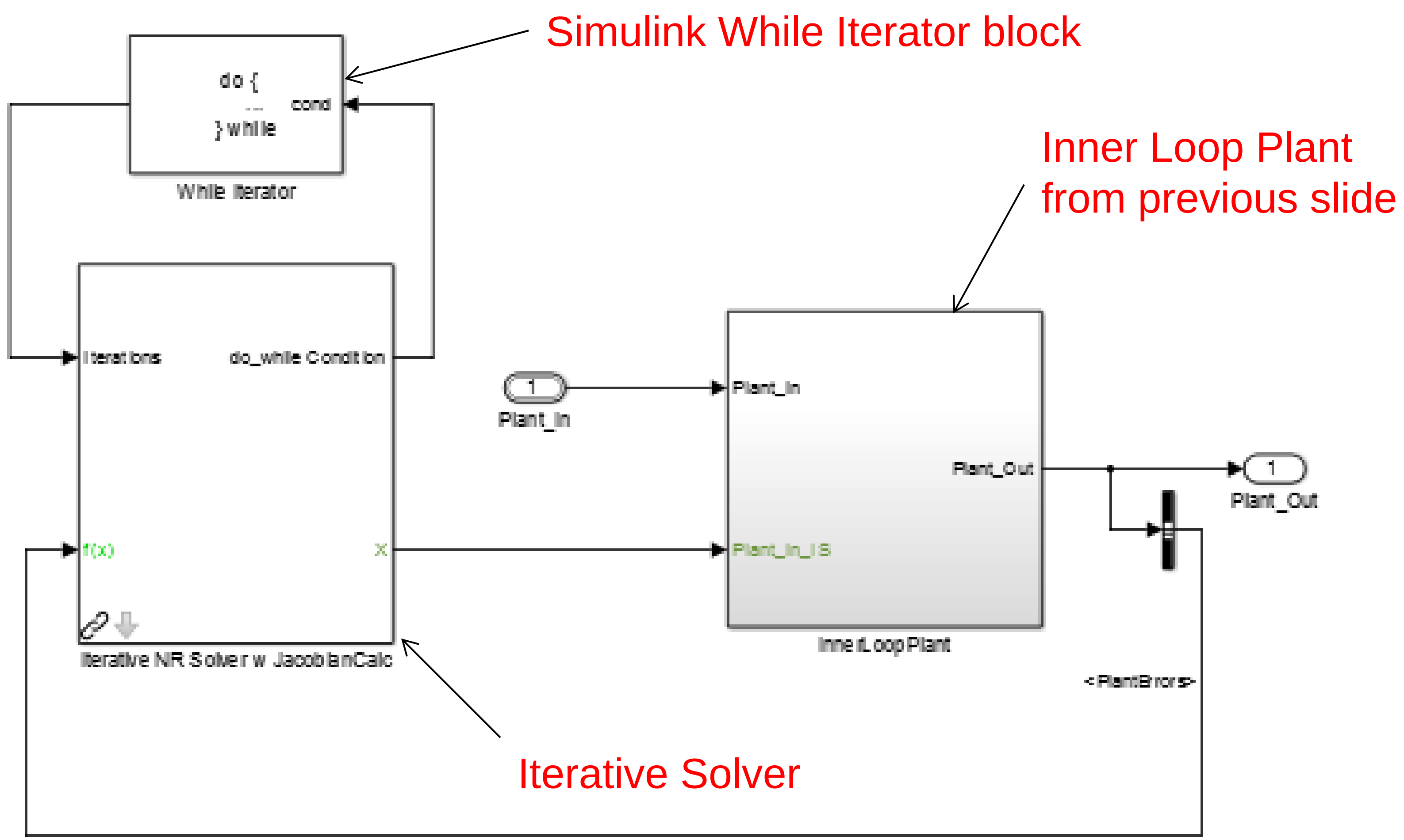


Turbojet plant model architecture made simple by T-MATS vectored I/O

Dynamic Gas Turbine Example: Creating the Solver

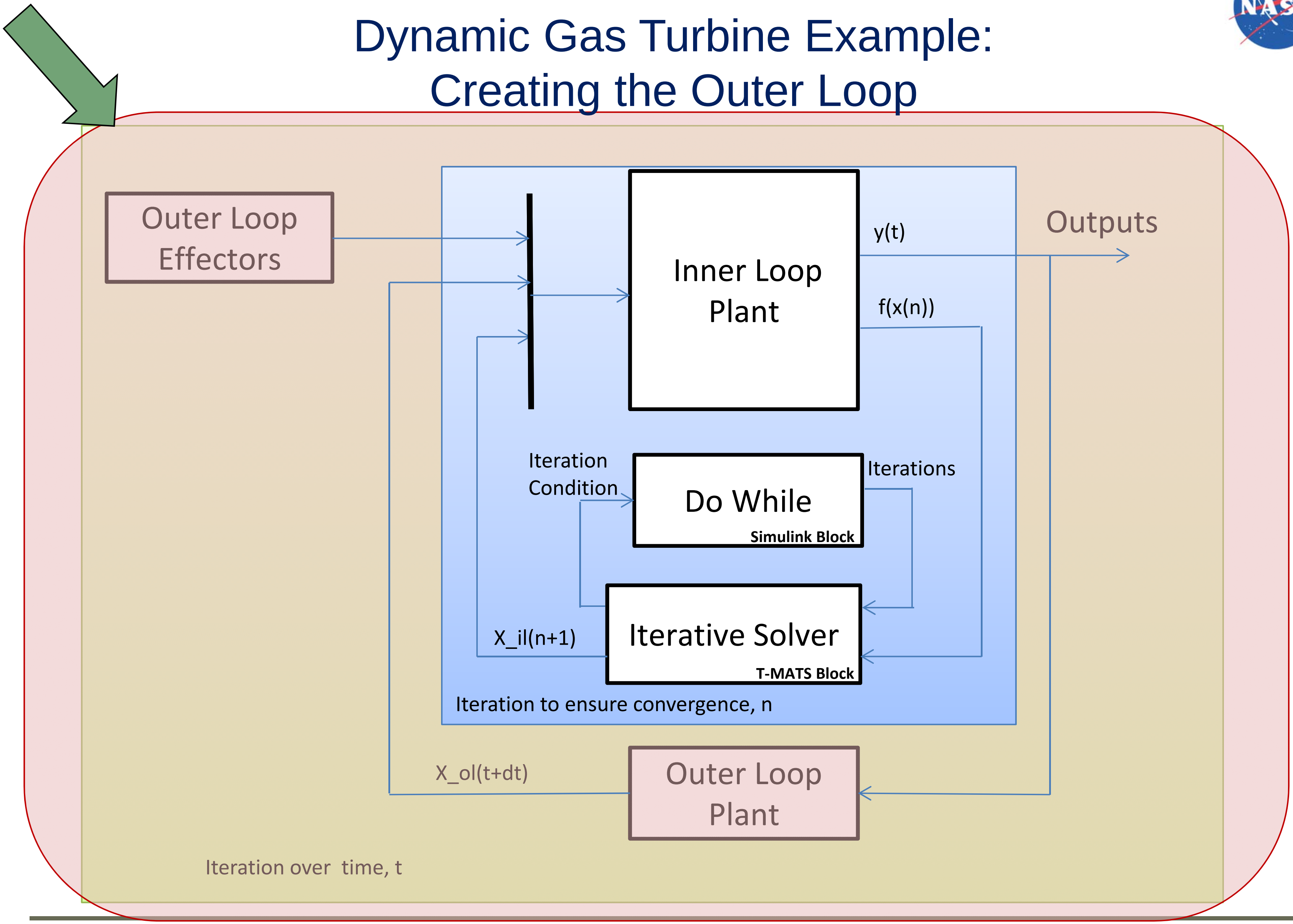


Dynamic Gas Turbine Example: Solver



Plant flow errors driven to zero by iterative solver block in parallel with While Iterator

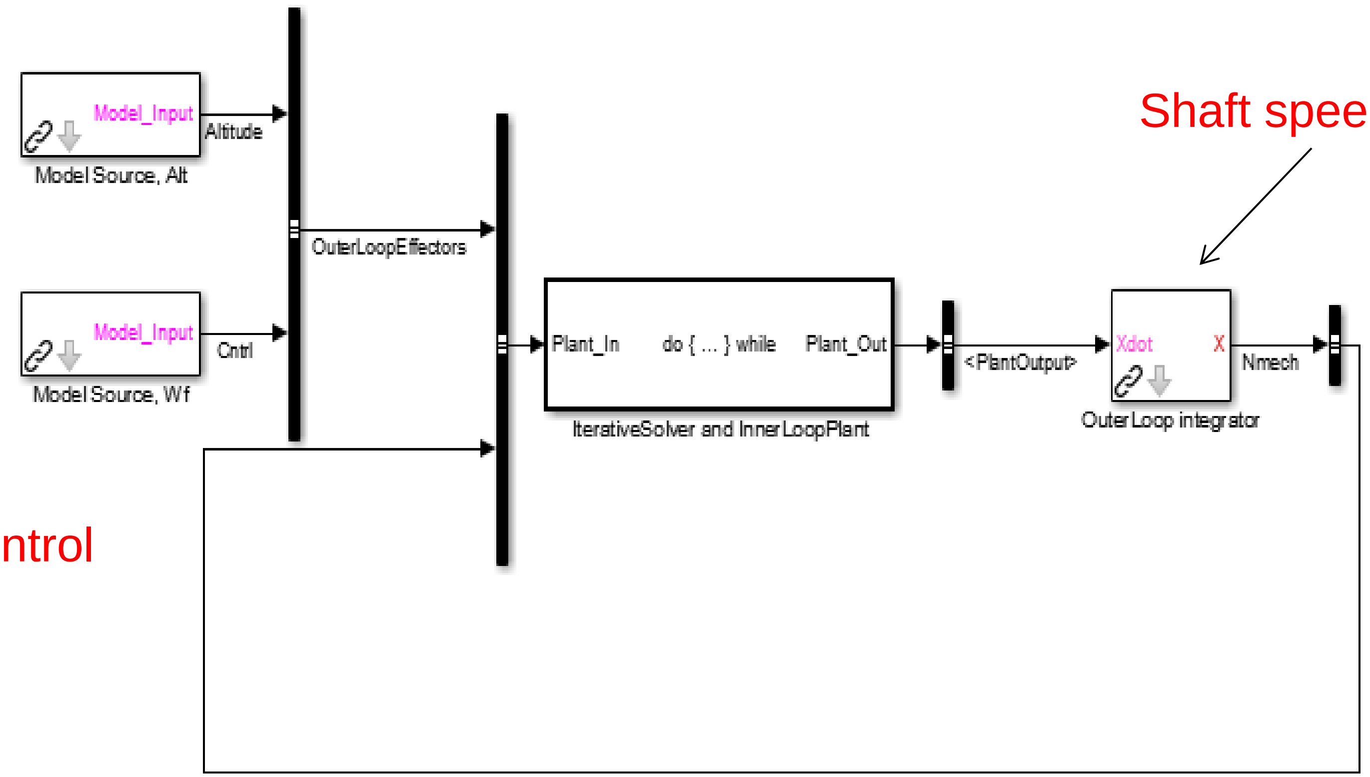
Dynamic Gas Turbine Example: Creating the Outer Loop



Dynamic Gas Turbine Example: Outer Loop Plant

Environmental conditions

Shaft speed integration

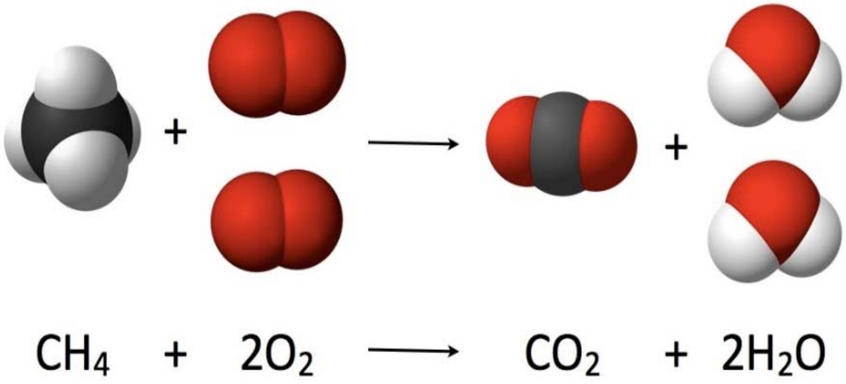


Simple Control System

Shaft integrator and other Outer Loop effectors added to create full system simulation

Post Initial Release Updates

- Integration with Cantera
  - Cantera models chemical kinetics, thermodynamics, and/or transport properties.
    - It is C++ based code with interfaces for python, MATLAB, C, and Fortran 90 (Code-based and open source)
    - Integration enables T-MATS to model fuel cells, engines using alternative fuels, etc.
      - Integration with T-MATS enables Cantera's capabilities to be utilized in a graphical plug and play modeling environment



https://en.wikipedia.org/wiki/File:Combustion_reaction_of_methane.jpg

Combustion reaction of methane

Simplification

T-MATS custom class based scripts and blocks simplify Cantera and allow easy creation of complex systems.

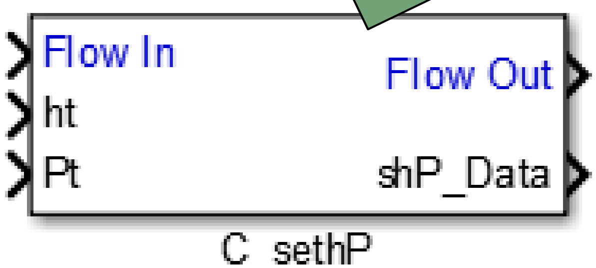
```
while  abs (lasterr)>.000000001 && count < 50
 set(fs,'Y',obj.CompVal_Can);
 set(fs, 'T', Ttg*5./9.,'P',Ptg*6894.75729 );
 equilibrate(fs, 'TP');
 htg = enthalpy_mass( fs )*.0004302099943161011;
 root = htg-htOut;
 sec_out = TMATSC.FlowDef.iterSecant( root, Ttg, last,
   lasterr, .1 );
 next = sec_out(1);
 last = sec_out(2);
 lasterr = sec_out(3);
 Ttg = next;
end
```

Cantera Code

```
TMATSC.set_hP(FlowObj,ht,Pt)
```

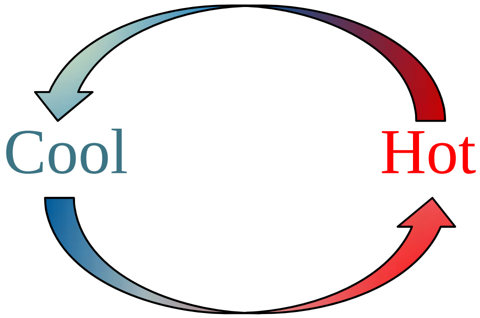
T-MATS Script

T-MATS Blocks



Additional Updates

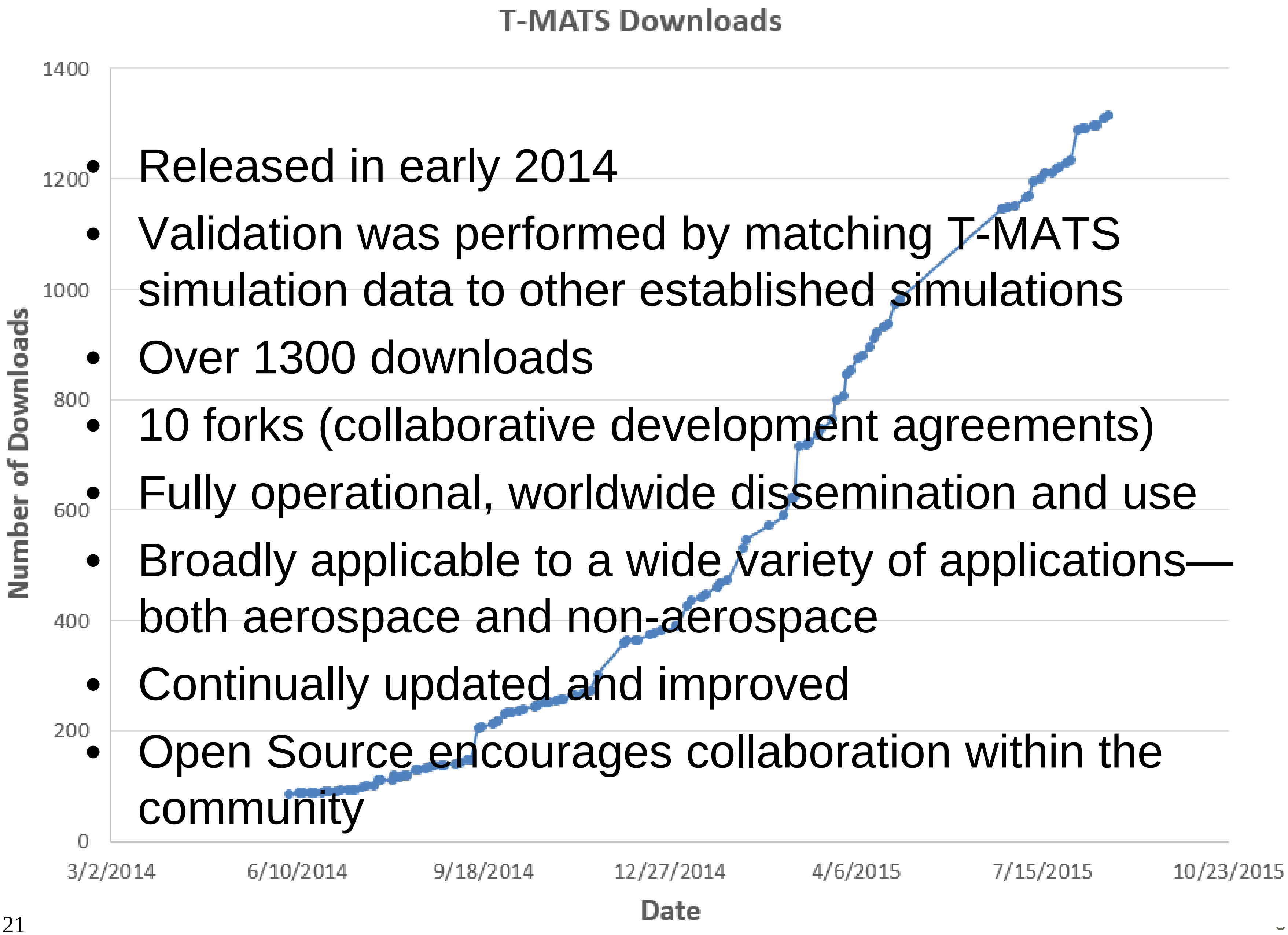
- New Capabilities
  - Heat Transfer Blocks
    - Lumped mass
    - Transient Conduction and Convection



- Additional Blocks

- Gear Box
  - Geared turbofan designs
- Alternative map structures for turbine blocks (psi and NPSS)
- Power Generator
  - Power applications
- Mixer
  - multi-flow path designs
- Heat Exchanger
  - inter-stage cooling
- Common gas turbine parameter calculations: Corrected W,N and SFC
- Numerical Linearization
  - dynamic linearization capable
- Inlet
- And MORE

Status



- Released in early 2014
- Validation was performed by matching T-MATS simulation data to other established simulations
- Over 1300 downloads
- 10 forks (collaborative development agreements)
- Fully operational, worldwide dissemination and use
- Broadly applicable to a wide variety of applications—both aerospace and non-aerospace
- Continually updated and improved
- Open Source encourages collaboration within the community

Recognition

- Appeared in a NASA tech brief article, 2014
- NASA Glenn Nominee for NASA's Software of the Year Award (SOYA), 2015
- MATLAB Central, File Exchange Pick of the Week Award, April 17^{th} 2015

"[T-MATS] fills a crucial niche in the Simulink modeling environment by providing an aero-thermal library."

Summary

- T-MATS offers a comprehensive thermodynamic simulation system
  - Thermodynamic system modeling framework
  - Automated system “convergence”
  - Advanced turbo-machinery modeling capability
  - Fast controller creation block set
  - Flexible chemical equilibrium and transport

Future Work

- Increase platform flexibility
  - Develop capability to export T-MATS models to C-code for real-time hardware-in-the-loop testing
  - Create tools for Utilizing Cantera capability in baseline T-MATS such as auto-generated off nominal parameter tables
  - Creation of user interface/visualization/analysis tools
  - Generic maps for fast prototyping
  - Creation of tools for better integration with NPSS
  - Added blocks to add capability to model Rockets more easily
  - Engine degradation handles
  - Engine heat soak handles

References

- Chapman, Jeffryes W., Lavelle, Thomas M., May, Ryan D., Litt, Jonathan S., Guo, Ten-Huei, “Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) User’s Guide,” NASA/TM—2014-216638, January 2014.
- Chapman, Jeffryes W., Lavelle, Thomas M., May, Ryan D., Litt, Jonathan S., Guo, Ten-Huei, “Propulsion System Simulation Using the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS),” AIAA 2014-3929, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014, also NASA/TM—2014-218410, November 2014.
- Zinnecker, Alicia M., Chapman, Jeffryes W., Lavelle, Thomas M., Litt, Jonathan S., “Development of a twin-spool turbofan engine simulation using the Toolbox for Modeling and Analysis of Thermodynamic Systems (T-MATS),” AIAA 2014-3930, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014, also NASA/TM—2014-218402, November 2014.
- Chapman, Jeffryes W., Lavelle, Thomas M., Litt, Jonathan S., Guo, Ten-Huei, “A Process for the Creation of T-MATS Propulsion System Models from NPSS data,” AIAA 2014-3931, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014, also NASA/TM—2014-218409, November 2014.
- Lavelle, Thomas M., Chapman, Jeffryes W., May, Ryan D., Litt, Jonathan S., Guo, Ten-Huei, “Cantera Integration with the Modeling and Analysis of Thermodynamic Systems (T-MATS)," AIAA 2014-3932, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014.