TIFAS: Topology Indepenent Framework for Aeromechanics Simulation

A novel approach to CFD and Multibody Dynamics software integration

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Introduction

What is "topology independent" modeling?

Why bother with topology independent modeling?

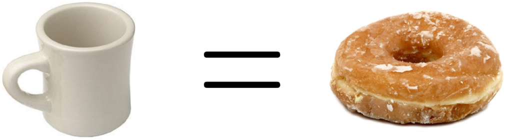
What is this silly TIFAS thing anyhow?

Outline

Outline

What is Topology?

Topology provides a foundation for understanding connectedness

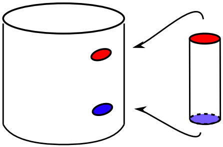


"A topologist is a person who cannot tell the difference between a coffee mug and a donut."

- We're interested in composing arbitrary systems from primitive components
- In this context, "topology" refers to how those components connect

How do we define a topology?

The simplest approach is to define a topology in terms of more primitive topologies.

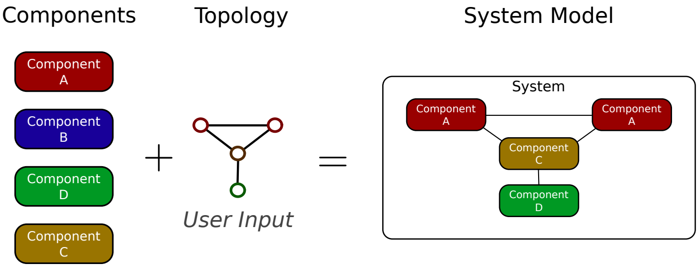


- Identify a collection of primitive objects with well defined topologies
- Identify faces, edges, points that join

Think quotient spaces.

Topology independent modeling?

Tools and algorithms that do not make any a-priori assumptions about the system topology



Outline

Not All Rotorcraft Share the Same Topology

- Multitude of vehicle configurations: conventional helicopter, tilt rotor, tandem, etc
- Rotor hub details
- Aerodynamic/vibration enhancements: e.g. flaps, slats, etc
- Novel control schemes: flaps, IBC, etc

Hard to find a common set of parameters to describe everything

Software Development and Reliability

Topology independent models reduce model development effort

- Facilitates distributed development and maintenance
- Isolated code units are easier to test and debug
- Possible to run basic fluid, structural, and aeroelastic benchmark test cases
- Reuse of tested component models improves system model reliability

Outline

TIFAS Project Description

Goals

- Develop a software framework for topology independent modeling of aeromechanics (CFD/CSD)

Constraints

- Allows solvers to be written in Fortran, C, C++, and use MPI
- Runs on both shared and distributed memory systems
- Compatible with POSIX compliant systems (UNIX/Linux)

Quality metrics

- Code is clearly written and well organized
- Minimizes effort required to add new capabilities (extensible)
- Minimizes effort and skill required to setup simulation
- Minimizes memory and CPU load

TIFAS Architecture Overview

A TIFAS simulation is roughly structured into 3 layers:

- Execution environment
  - Underlying operating system (external)
  - Parallel runtime environment (external, optional)
  - Execution Monitor
- Simulation management
  - SIMMAN: SIMulation MANager
  - Solver Modules
  - Requisition Agents
  - Solver (external)
- Inter-Solver Connectivity
  - Network
  - Surrogates
  - Observers
  - Maps

Fluid and structural solvers are essentially “plug-ins”.

Solver

Definition (Solver)

A solver is an algorithm combined with a data structured that has been designed to model the behavior of a physical body or medium.

Examples:

- A CFD solver such as OVERTURNS, OVERFLOW, SU^2
- A multi-body dynamics solver such as Rodymol, MBDyn, DYMORE
- A vortex lattice model

Comments:

- A solver is external component of TIFAS (simplifies devel and licensing)
- Solvers are compiled into dynamically loaded libraries (simplifies licensing)
- TIFAS defines an API that each solver must implement
- The API is such that TIFAS can control module initialization, deallocation, and time step synchronization.
- Upon initialization, solvers are given a handle to a Requisition Agent, through which each solver obtains access to TIFAS resources

Solver C API

```c
/*******************************************
 * All functions return an integer return code. *
 * Non-zero value indicates an error.           *
 *******************************************/

// Initializes solver module.
int tifas_module_init(RequistionAgent* agent /* in */);

// Advances the solver by one time step
int tifas_module_step();

// Deallocates heap allocated memory, if any.
int tifas_module_del();
```

Choose C as Solver API language because:

- Most solvers appear to be written in C, Fortran, or C++
- Fortran (2003) and C++ provide intrinsic mechanisms for C interoperability
- C has well defined ABI

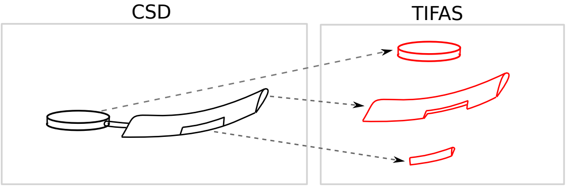
Surrogates

Definition

A surrogate is an object modeled after a primitive type of structural component or load, that responds to requests for information on behalf of a solver.

- Surrogates are a generic extension of a Solver's interface
- Solvers do not share surrogates
- Each solver module is responsible for updating its surrogates when change in state occurs.

Example:



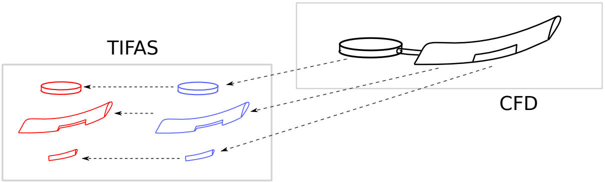
Observers

Definition

An observer is an object providing access to external information required by a solver.

- Each observer is assigned to a specific data source.
- Data sources include surrogates and maps
- Observers can function as a “window” by which a solver can view another solver’s data
- A single data source may be viewed by multiple observers

Example:



Maps

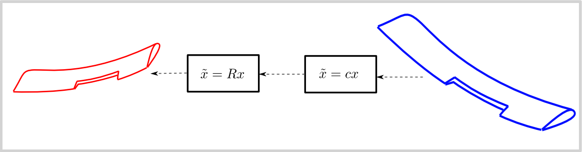
Definition

A Map is an object that applies a static transformation to the output of a data source.

- Is associated with a unique surrogate and observer pair
- Implements surrogate and observer interfaces
- May be composed (chained) to form a composite transformation

Example:

TIFAS

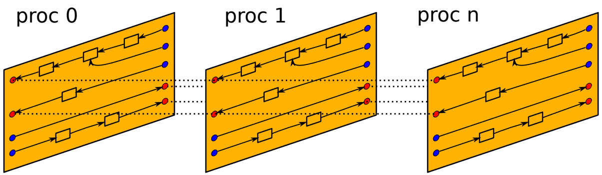


Network

Definition

A Network is a collection of surrogates, maps, and observers linked into the form of directed graphs with a surrogate as its origin.

- Constructs itself from a user description of system topology
- Is mirrored across all processes
- Mirrored surrogates share memory



Requisition Agent

Definition

The object by which a solver requests access to TIFAS resources during initialization is called a Requistion Agent.

- A unique Requisition Agent is created for each solver module
- Each agent may monitor and restrict access to resources on a per solver basis
- Facilitates detection of user configuration errors
- May be used in future to enable automated network configuration

Example:

```
int tifas_module_init(RequistionAgent* agent){
                    ...
    // Get handle to a blade surrogate...
    Object* blade_surrogate = agent.request_surrogate("BLADE_1");
    // Get handle to an airloads observer...
    Object* blade_airloads = agent.request_observer("AIRLOADS_1");
                    ...
    return 0;
}
```

Solver Module

Definition

A Solver Module is an abstract model of a Solver.

- An internal (C++) representation of a solver (external component)
- Contains mechanisms to find and load a solver from disk
- Maps error codes returned from solver functions (C) into TIFAS exceptions (C++)

Modeling solvers as modules instead of classes simplifies the reuse of existing CFD and multi-body dynamics software–which may contain statically allocated data (i.e. global variables).

SIMMAN: SIMulation MANager

Definition

The SIMulation MANager (SIMMAN) is the object that coordinates and monitors all elements of a simulation.

- Creates a network on each processor
- Instantiates all Solvers (passing each a Requisition Agent)
- Executes solvers in sequential fashion (staggered coupling)

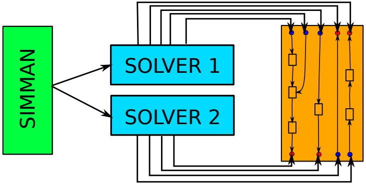


Figure : Only 2 solvers shown for clarity.

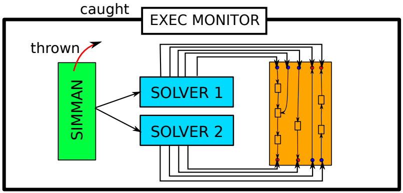
(Recall the game Simon Says)

Execution Monitor

Definition

The Execution Monitor is a driver program that loads inputs, instantiates SIMMAN, and catches runtime errors.

- A small program that “boots” SIMMAN, then waits for an exception
- Could be easily replaced by a different driver program



TIFAS DSL (user input)

A declarative, Domain Specific Language (DSL), used as user input.

Declaration of surrogates, maps, observers

```
<object name>
{
    type_name = <type name>;
    <property name> = <property value> ;
    [ <property name> = <property value>;]
    [ ... ]
}
```

Network topology syntax:

```
<surrogate name> -> [ <map name> -> [...]]] <observer name> ;
```

DSL could be easily mapped to a graphical language/interface (e.g. LabView, Simulink).

TIFAS Scripting Example

```
# Declare surrogates, maps, observers...
csd:beam{ type_name=FlexibleBeam; host_rank=0;  }
cfd:blade_mesh{ type_name=FlexibleBeamObserver; }
unit_conv{
    type_name=FlexibleBeamUnitConversion;
    config_file=unit_conv.in;
}
frame_conv{
    type_name=FlexibleBeamCoorRotation;
    config_file=frame_config.in;
}

# Define network topology...
csd:beam -> unit_conv -> frame_conv -> cfd:blade_mesh;
                         frame_conv -> freewake:blade_motion;
```

Outline

Language Choice

TIFAS is implemented in C++

- Desire OOP language: modular, extensible, verifiable, maintainable (DRY-principle)
- Mature compilers available for virtually all platforms
- ISO regulated - maintains backwards compatibility
- Can directly use libraries supporting C ABI

Connectivity Library provides C++, C and Fortran API's

Connectivity Library

Contract Programming

- A design scheme in which formal interface definitions are central to a program's structure
- The interfaces need not model a well defined object type
- Preconditions, post-conditions, and invariants may be used to ensure that a particular object meets spec
- Is found to work well for frameworks modeling servant-client relationships

In TIFAS:

- Combine C++ pure abstract classes with RTTI to emulate Contract Programming
- All surrogates, maps, and observers derive from a generic "object" type, and implement a specific set of predefined interfaces.
- Use of contracts simplifies implementation of Network as well as the test suite

Parallelization of the TIFAS Connectivity Library

MPI-2 Remote Memory Access (RMA)

- An alternative to traditional message passing
- Uses separate mechanisms for data transfer and synchronization
- Communication is by way of "memory windows"
- Synchronization schemes: active target (e.g. fences), passive target (locks)

- An identical Network is created on all MPI processes
- Each surrogate creates a memory window that is shared with its clones on other processes
- Surrogates share information with their respective clones by reading/writing to their memory window

Outline

Summary

Topology

- Connectedness: a geometric property more fundamental than shape or size

Topology Independent Modeling

- Regards topology definition as a user input
- Mitigates the need to find a common parameter space

TIFAS

- A framework for topology independent CFD/CSD analysis
- Solvers communicate by way of surrogates and observers
- Time synchronization is managed separately by SIMMAN
- System topology is described using a high-level, declarative, DSL
- TIFAS is implemented in C++

Future Work

Items on the TODO list:

- Look into releasing TIFAS under open source license
- Implement virtual work preserving load transfer algorithms
- Profile framework to better understand “bottlenecks”

Possible directions for future research:

- Revisit the choice of “pull” versus “push” model
- Investigate alternative concurrency models
- Hybrid CPU/GPU extensions
- Algorithms for automatic configuration of unit and frame conversions
- Alternative DSL’s for topology independent modeling:
  - Facilitates formal correctness proofs
  - More robust grammar (i.e. stronger syntax checking)

Questions?