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The Final Report on:

Development of a Dynamically Configurable, Object-Oriented Framework for Distributed, Multi-modal Computational Aerospace Systems Simulation

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October 30, 2003

Summary

This report describes the progress made in the first two years (Sept. 1, 1999 to Aug. 31, 2001) of work at The University of Toledo under the NASA Information Technology (IT) Program grant number NAG-1-2244. This research was aimed at developing a new and advanced simulation framework that will significantly improve the overall efficiency of aerospace systems design and development. The project was originally a three-year project with specific tasks to be completed in each of the three years. However, the project was funded only for two years and the third year's funding was thus unavailable to complete the tasks planned in the original proposal. At the end of each year, a progress report was sent to the Grant Monitor, Mr. Wayne Gerdes. The reports are reproduced in Appendix A. The work accomplished under the grant is already described in the progress reports and accordingly will not be repeated here. Four papers, two journal papers and two conference papers were published primarily based on the work done on this project. Three of these publications occurred after the second year report had been submitted; hence a copy of these papers is provided for completeness in Appendix B. The second journal paper entitled "On XML-based Integrated Database Model for Multidisciplinary Aircraft Design" is accepted for publication and is scheduled to appear in AIAA Journal of Aerospace Computing, Information, and Communication in 2004.

APPENDIX A: Reports

A first year progress report on:

Development of a Dynamically Configurable, Object-Oriented Framework for Distributed, Multi-modal Computational Aerospace Systems Simulation

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Summary

This report describes the progress made in the first year (Sept. 1, 1999 to Aug. 31, 2000) of work at The University of Toledo under the NASA Information Technology (IT) Program grant number NAG-1-2244. This research is aimed at developing a new and advanced simulation framework that will significantly improve the overall efficiency of aerospace systems design and development. This objective will be accomplished through an innovative integration of object-oriented and Web-based technologies with both new and proven simulation methodologies. The basic approach involves three major areas of research:

- Aerospace system and component representation using a hierarchical object-oriented component model which enables the use of multimodels and enforces component interoperability.
- Collaborative software environment that streamlines the process of developing, sharing and integrating aerospace design and analysis models.
- Development of a distributed infrastructure which enables Web-based exchange of models to simplify the collaborative design process, and to support computationally intensive aerospace design and analysis processes.

Research for the first year dealt with the design of the basic architecture and supporting infrastructure, an initial implementation of that design, and a demonstration of its application to an example aircraft engine system simulation.

Year 1 Accomplishments

Work was begun in several areas during the first year of this three year grant. Major results are summarized below. A more comprehensive description of the methodology and initial accomplishments, along with an overall vision statement of our long term research goals, was published in Ref. 1.

Common Model Framework

An object-oriented domain framework for representing aerospace components, systems and subsystems has been developed. The framework, which we call the Common Model Framework (CMF), provides the foundation for the Denali[1] aerospace simulation system. The framework formalizes an approach for abstracting aerospace domain physical structure and mapping it to the computational domain. As shown in Figure 1, aerospace systems, such as an aircraft, are hierarchically decomposed (Fig. 1b) into subsystems and components (e.g., fuselage, engines, vertical stabilizer, etc.), which are then abstracted using a control volume approach (Fig. 1c). The control volumes provide both a physical geometry representation as well as a convenient mechanism for mathematical modeling. Each component can be further decomposed to identify more basic components. The most basic components may be represented in the computational domain by an object class. Following the Denali CMF architecture, the more basic classes can be instantiated and the various objects combined to form more complex objects. This object composition provides a powerful and flexible mechanism for modeling and simulating aerospace systems, allowing complex aerospace systems to be composed in the same familiar manner as the physical system.

There are four basic entities in the Denali architecture: *Element, Port, Connector* and *DomainModel* (see Fig. 1d). The Java™ interface **Element** represents a control volume, and defines the key behavior for all engineering component classes incorporated into Denali. It declares the core methods needed to initialize, run and stop model execution, as well as methods for managing attached **Port** objects. Classes implementing this interface generally represent physical components, such as a compressor, turbine blade, or bearing, to name a few. However, they may also represent purely mathematical abstractions such as a cell in a finite-volume mesh used in a CFD analysis. This flexibility permits the component architecture to model a variety of physical systems.

An **Element** may have zero or more **Port** objects associated with it. The **Port** interface represent a surface on a control volume through which some entity (e.g., mass or energy) or information passes. **Ports** are generally classified by the entity being transported across the control surface. For example, a Compressor object might have two **FluidPort** objects—representing the fluid boundaries at the Compressor entrance and exit—and a **StructuralPort** object, representing the control surface on the Compressor through which mechanical energy is passed (from a driving shaft).

1. Not an acronym.

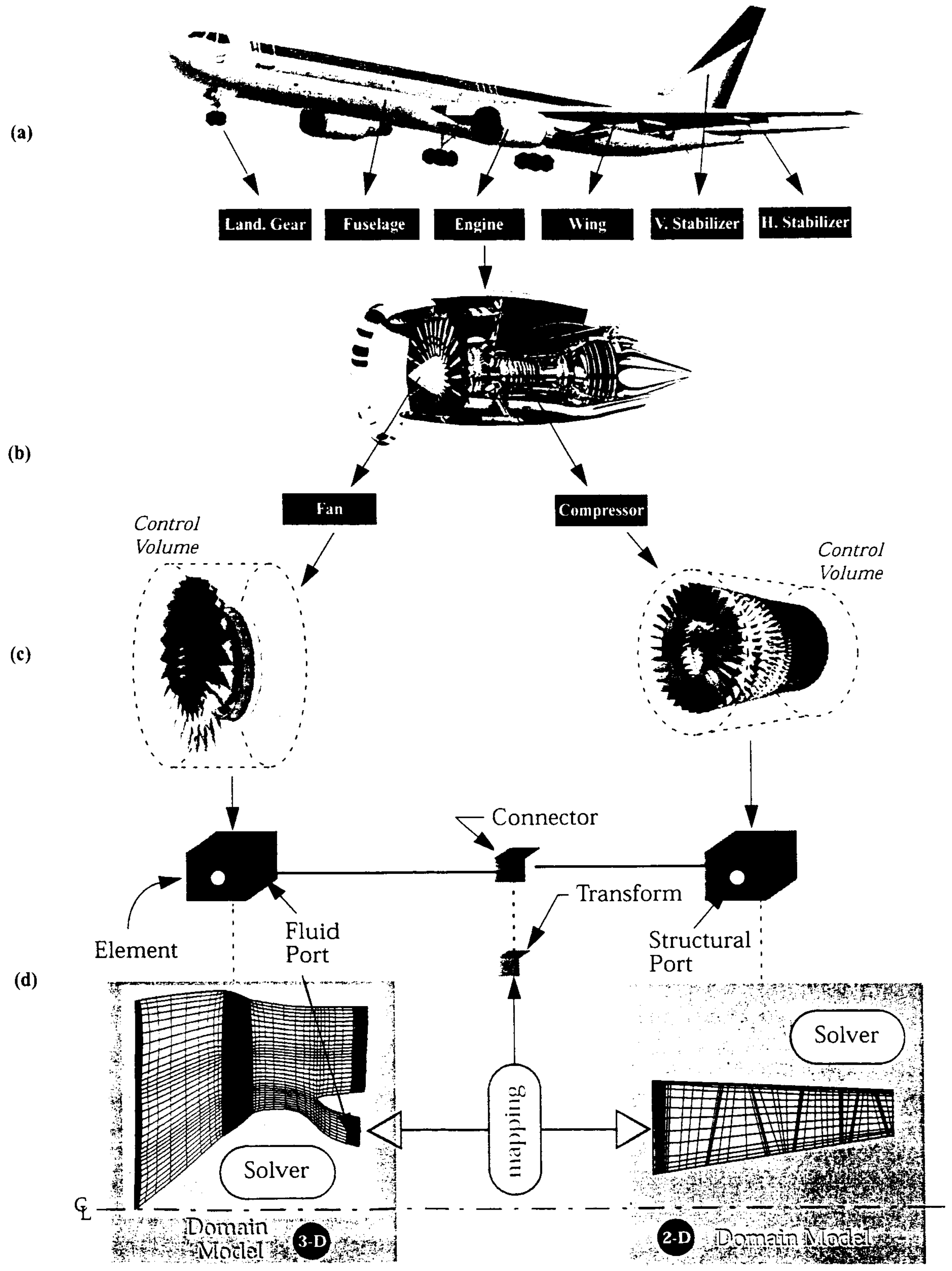


Figure 1: Mapping of aerospace physical domain to computational framework.

The common boundary between consecutive control volumes is represented by a **Connector** object. The interface **Connector** permits two **Element** objects to communicate by passing information between connected **Port** objects (see Fig. 1d). It is also responsible for data transformation and mapping in situations where the data being passed from **Ports** is of different type. The need for such data transformation can range from simple situations, such as conversion of data units, to very complex ones involving a mismatch in model fidelity (e.g., connecting a 2-D fluid model to a 3-D fluid model) or disciplinary coupling (e.g, mapping structural analysis results from a finite-element mesh to a finite-volume mesh used for aerodynamic analysis). For all but the simplest cases, the algorithms needed to perform the data transformation or mapping will tend to be very complex. To improve reusability, **Connector** delegates transformation/mapping responsibilities to a separate **Transform** object (see Fig. 1d) which encapsulates the necessary intelligence to expand/contract data and map data across disciplines.

The **DomainModel** represents the mathematical model used to define component behavior. During component design and analysis, many different models (i.e., multimodels) are used. During preliminary design the models are relatively simple and may be solved analytically or using basic numerical methods. However, models used in latter phases of design can be quite complicated. In these cases, approximate solutions are obtained by discretization of the equations on a geometrical mesh and applying highly specialized numerical solvers. The presence of these complex mathematical models and the numerical tools needed to solve them suggest that it is desirable to encapsulate these features and remove them from the **Element** structure. This enhances the modularity of **Element**, allowing new **Element** classes to be added without regard to the mathematical model used, and conversely to add new models without affecting the **Element** class. To achieve this, Denali utilizes the Strategy design pattern to encapsulate the mathematical model in a separate object. The benefit of this pattern is that families of similar algorithms become interchangeable, allowing the algorithm—in this case the **DomainModel**—to vary independently from the **Elements** that use it. This admits the possibility of run-time selection of an appropriate **DomainModel** for a given **Element**; however, this is currently not used in Denali. Furthermore, encapsulating the **DomainModel** in a separate object also encourages the "wrapping" of pre-existing, external software packages. For example, the Fan **DomainModel** in Fig. 1d might "wrap" a pre-existing three-dimensional Navier-Stokes or Euler flow solver to provide steady-state aerodynamic analysis of fluid flow within the Fan. This approach allows proven functionality of existing software analysis packages to be easily integrated within an **Element**.

The standard object interfaces of the Denali CMF ensure that each component object interoperates with other component objects. This is essential for providing a stable modeling environment which allows complex models to be developed using object composition and class inheritance. Furthermore, the standard interfaces of the CMF architecture provide a "pluggable" architecture wherein new components can be added at runtime.

As an example application of the CMF, a model of a the NASA/GE Energy Efficient Engine (EEE) gas turbine aircraft engine was created. **Elements** representing the inlet, fan, compressor, combustor, shafts, turbines, nozzle and ducts in a turbofan engine were developed. The **DomainModel** for each **Element** was developed using a zero-dimensional mathematical treatment. Furthermore, only an aerothermodynamic disciplinary analysis was used. At this level of fidelity and discipline, component behavior was defined by the unsteady, space-averaged forms of the aerothermodynamic conservation equations. Empirical data, in the form of performance maps, were used to define operating behavior for rotating components, such as Compressors and Turbines. The component objects were combined using appropriate zero-dimensional fluid and mechanical **Port** and **Connector** objects. A Newton-Raphson numerical execution scheme (also provided as part of the Denali system) was used to sole the model equations and simulate both steady and unsteady engine operation. Results of the tests were validated against other existing FORTRAN gas turbine engine simulation programs.

Connection Services Framework

Aerospace design and analysis requires the interaction of many people at different geographic locations. Even if these individuals are part of the same company, today's increasingly international business environment and corporate structures requires us to assume that the participants may not be at the same location. Moreover, strategic partnerships between companies (even those competing in the same business domain) are becoming more common place requiring additional interaction across company boundaries. As a result, it is important that our simulation framework enable users to collaborate by sharing models and data in a heterogeneous work environment.

Denali supports the exchange of models through the use of *mobile code*. Mobile code is defined as program code which can be transferred from one computer to another and executed (without recompilation) on the receiving computer. An example of this is the Java byte-code which is executed on the receiving machine by a Java Virtual Machine interpreter. Denali utilizes this feature to allow designers to create, compile, verify and share Java-based component models. Following the design guidelines specified by the CMF, aerospace components are created, placed on a Web-server and downloaded to a Denali client. Once loaded to the client, the model can be combined without additional programming effort to form a new model.

In aerospace design and analysis, as in many other engineering domains, access to distributed resources is critical. The computationally intensive nature of higher fidelity analysis codes (such as Computational Fluid Dynamics) require access to high performance supercomputers or networks of workstations. Furthermore, the use of legacy code in aerospace design and analysis often require access to codes that are constrained to run on specific architectures or operating systems. As a result, it is important that our simulation framework enable users to access the appropriate computing resources for the target application.

The Denali Connection Services Framework (CSF) provides the necessary infrastructure to enable *transparent* access to distributed resources using both Web-based exchange of models, and distributed object service. Web-based models—models written entirely in Java—are created, compiled, verified, tested and placed on an HTTP web server where they can be accessed from a Denali client. Non-Java models, such as legacy FORTRAN software, which are fixed to a particular location due to code size, computing architecture or proprietary reasons, are placed on remote machines and wrapped by a Java object. This wrapper defines an interface to the legacy code and acts as a proxy, enabling the legacy code to be viewed as a local object. As with the Web-based models, the Java wrapper for the remote legacy code is placed on a Web server so that it may be downloaded to the Denali client.

The Denali client, positioned on a user's workstation or personal computer, locates available Web-based and remote models by querying one or more well-known naming or directory service. Using a Component Browser, a user can browse the objects and data stored in a naming or directory service (see bottom-right corner of Fig. 2). Denali currently supports access to common naming and directory services, such as NDS, LDAP, CORBA Naming Service (COS Naming), and RMI Registry, through the Java Naming and Directory Interface (JNDI). JNDI is an API that provides an abstraction that represents elements common to the most widely available naming and directory services. JNDI also allows different services to be linked to together to form a single logical namespace called a federated naming service. Using the Component Browser, Denali users are able to navigate across multiple naming and directory services to locate simulation data, objects and components.

Currently, we mainly use an LDAP (Lightweight Directory Access Protocol) service which provides both naming (objects are referred by their name) and directory (objects are stored in hierarchies) access. We utilize the OpenLDAP software, an open-source implementation of the LDAP protocol, running on a UNIX workstation in our lab. Rather than storing the model objects in the LDAP service, we chose to store only attributes of the component. This reduces the need to store and transfer large objects from the LDAP, and allows models to be located by searching for keywords corresponding to certain attributes. For example, for each model component, we define the class name, the model author, model creation and expiration date, and the URL of the model code, to name a few. When a component is selected from the LDAP, the Java byte-codes are downloaded from the Web server defined by the component's URL attribute. On the client machine, the byte-codes are dynamically loaded and used to create an instance of the model.

For security purposes, the Component Browser requires users to authenticate themselves before they can retrieve any information from a naming or directory service. Once authentication has been successfully completed, the user can browse or search (using attribute keywords) the entire namespace (subject to any authorization restrictions). Authentication and authorization capabilities are provided through JNDI and the Java Authentication and Authorization Service (JAAS) framework. These tools allow the Component Browser to remain independent from the underlying security services, which is an important concern when working in a heterogeneous computing environment such as the Web.

Access and utilization of both Web-based and remote legacy models have been tested successfully using the Denali CSF. Component models for the EEE gas turbine engine model were placed on a Web server (mime1) located in our lab. Each component model, with the exception of the Combustor, was defined as a Web-based model (i.e., written in Java). For this test, a FORTRAN Combustor model, representing non-Java legacy codes, was written, compiled and placed on a second machine (mime2). A Java wrapper, acting as a proxy for the Combustor model, was written, compiled and placed on the Web server (mime1). Deployment of each component also included registering component attributes with the LDAP service running on a third machine (mime3). A Denali client, operating on a fourth machine (mime4), was then used to access and construct the EEE engine system model using the Denali Visual Assembly Framework, which is described below.

Visual Assembly Framework

The Visual Assembly Framework (VAF) provides a configurable, extensible graphical interface for constructing and editing Denali component and system models. Aerospace component objects, placed on Web servers and registered in the LDAP service are graphically manipulated in the VAF to create new models, or edit existing models. Icons, representing individual engine components (i.e., **Elements**), are selected from the Component Browser, dragged into a workspace window, and interconnected to form a schematic diagram (see Fig. 2). Dragging an icon from the Component Browser to the workspace window causes the selected software component to be downloaded from the Web server to the client machine. Components comprised entirely of Java classes are downloaded from a Web server to the local file system where the byte-codes are extracted from the JAR file, loaded into the Java Virtual Machine and instantiated for use in Denali. Components developed in other programming languages are not downloaded, but remain on the server. Instead, the proxy object, representing the component, is downloaded and used to connect to the remote component using the Java Remote Method Invocation (RMI) substrate.

Denali supports the creation of hierarchical component models, and an icon can represent both a single component or an assembly of components. A component with subcomponents is called a composite or structured component. Components that are not structured are called primitive components, since they are typically defined in terms of primitives such as variables and equations. Composite components are represented by a **CompositeElement** class, which is part of the **Element** hierarchy. The class structure, based on the Composite design pattern, effectively captures the part-whole hierarchical structure of the component models, and allows the uniform treatment of both individual objects and compositions of objects. Such treatment is essential for providing the object interoperability needed to perform Web-based model construction by composition.

Figure 2 shows a composite model representing an aircraft turbofan engine. The icon labeled Core is a composite of components which are displayed in the lower schematic. Each icon has one or more small boxes on its perimeter to represent its Ports. Connecting lines are drawn between the ports on different icons by dragging the mouse. A **Connector** object having the correct **Transform** object needed to connect the two ports is created automatically by Denali. Each icon has a popup menu which can be used "customize" the attributes of its **Element**, **Port** and **DomainModel** objects. When selected, a graphical **Customizer** object is displayed (see upper-right corner of Fig. 2), which can be used to view or edit the selected objects attributes. The visual assembly interface also provides tools for plotting (see the lower-left corner of Fig. 2), editing files, and browsing on-line documentation.

Using the VAF interface, the EEE component models were successfully downloaded from the Web server (mime1),and combined graphically to form an EEE engine model in the VAF. A Newton-Raphson numerical execution scheme (provided as part of the Denali system) was used to solve the system of equations and simulate both steady and unsteady engine operation. Results of the tests were validated against other existing FORTRAN gas turbine engine simulation programs.

Currently the VAF interface is implemented as a Java application rather than a Java applet. This was done for two reasons: 1) Java applications are easier to develop than applets, since they do not require explicit security controls (i.e., signing); and. 2) browser technology needed to run applets is not up-to-date. Also, a new product. called Java Web Start is now available (in beta form) which allows users to download Java *applications* which run on the desktop, in much the same manner as applets, but do not require a Web browser. We are currently experimenting with the Java Web Start to evaluate its use with Denali.

Publications Resulting from Work Supported by This Grant

[1] Reed, J. A., Follen, G. J., and Afjeh, A. A., "Improving the aircraft design process using Web-based modeling and simulation, "*ACM Transactions on Modeling and Computer Simulation*, Vol. 10, No. 1, 2000, pp. 58-83, (special issue on Web-based Modeling and Simulation).

Plans for Year 2

Common Model Framework

- The majority of work in year 2 will focus on the addition of geometry data to models. Specifically, we plan to work on providing direct access to CAD native geometry data. Our plan is to use a middleware layer being developed at MIT to allow us to access a variety of CAD packages using a common API. Access to CAD geometry will allow us to enhance our visualization capabilities.

- We plan to test integration of several database management systems with Denali. This had been slated for yr. 1, but was postponed until yr. 2 to more fully explore the use of new approaches to saving models, such as using XML.

- We also plan to obtain existing airframe models for study. These will be integrated within the Denali simulation system in year 3.

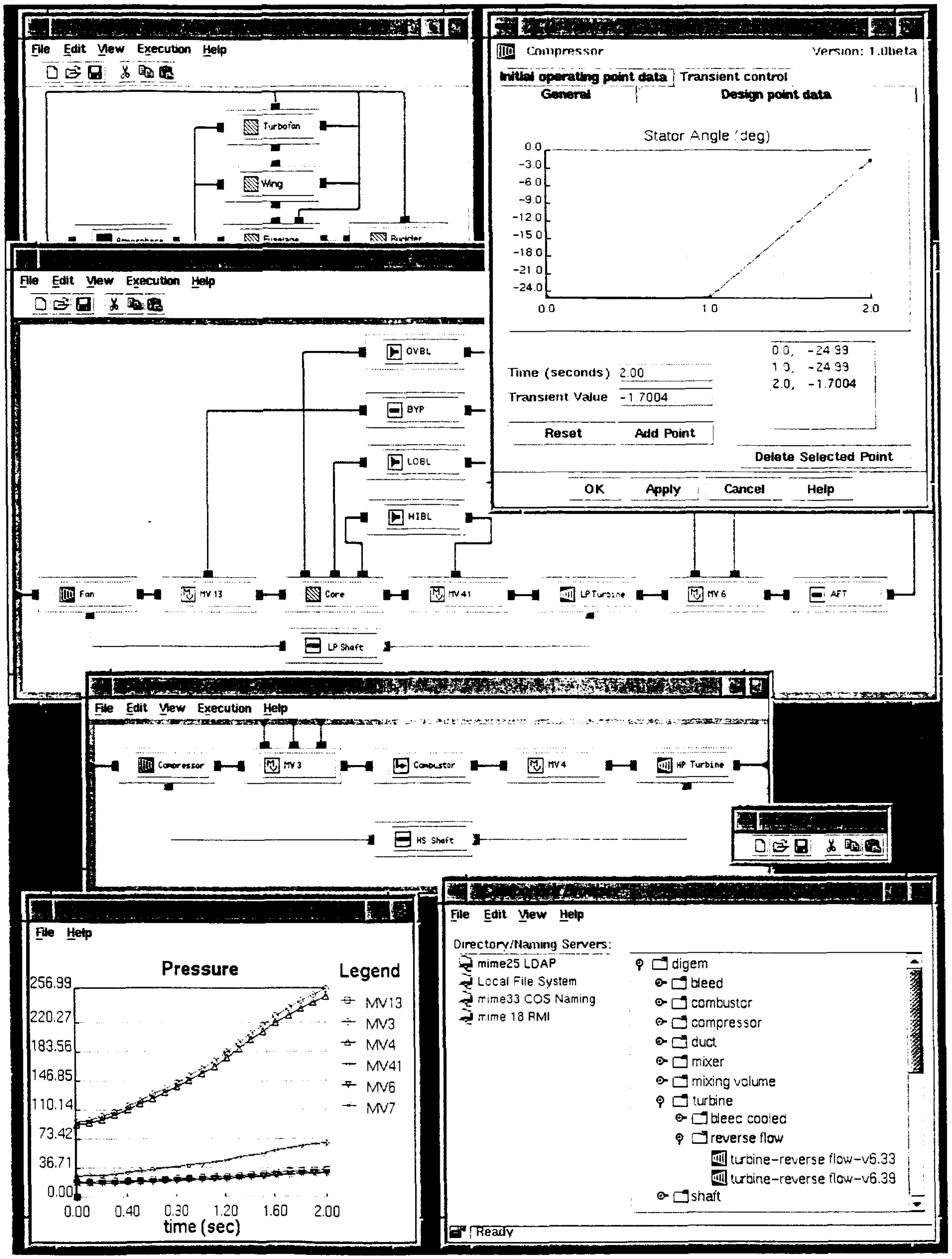
Connection Services Framework

- We will continue to improve non-mobile code services. Specifically, we are working on developing generalized specifications for wrapping legacy codes common in the aerospace domain. These include CFD and FEA tools, as well as numerical solvers and optimizers.

Visual Assembly Framework

- We will work on integration of CFD and geometry visualization. We will examine the possibility of integrating an existing visualization tool, or creating a new Java-based visualization tool to display geometry and flow data.

- We will continue to enhance and refine our VAF design to make it more intuitive and easier to use. We hope to provide a beta version of the Denali system to users at aerospace companies and NASA centers for evaluation. Feedback from these beta testers will be used to enhance the Denali VAF (and other parts of Denali).



Time (seconds) 2.00
Transient Value -1.7004

0.0, -24.99
1.0, -24.99
2.0, -1.7004

Figure 2: Denali Visual Assembly interface showing integration of engine model.

A second year progress report on:

Development of a Dynamically Configurable, Object-Oriented Framework for Distributed, Multi-modal Computational Aerospace Systems Simulation

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Summary

This report describes the progress made in the second year (Sept. 1, 2000 to Aug. 31, 2001) of work at The University of Toledo under the NASA Information Technology (IT) Program grant number NAG-1-2244. This research is aimed at developing a new and advanced simulation framework that will significantly improve the overall efficiency of aerospace systems design and development. This objective will be accomplished through an innovative integration of object-oriented and Web-based technologies with both new and proven simulation methodologies. The basic approach involves three major areas of research:

- Aerospace system and component representation using a hierarchical object-oriented component model which enables the use of multimodels and enforces component interoperability.

- Collaborative software environment that streamlines the process of developing, sharing and integrating aerospace design and analysis models.

- Development of a distributed infrastructure which enables Web-based exchange of models to simplify the collaborative design process, and to support computationally intensive aerospace design and analysis processes.

Research for the second year focused on enabling models developed in the *Denali* software environment to directly access CAD native geometry. Access to CAD geometry is essential to generate mesh for use in fluid and structural analysis of aerospace systems, as well as visualization of analysis results. Furthermore, a *geometry-centric* modeling approach, as employed in this work, simplifies use of these and other tools in a multidisciplinary design process. Finally, *direct* access to CAD native geometry, compared to geometry described in intermediate forms (e.g., IGES[1], STEP[2], STL[3], etc.), is more robust.

Year 2 Accomplishments

Introduction

Computational simulation plays an essential role in the aerospace design process. Computer-aided design (CAD) methods are the basic tool for definition and control of the configuration, and CAD solid modeling capabilities enable designers to create virtual mockups of system to verify that no interferences exist in part layouts. Similarly, structural analysis is almost entirely performed using computational tools employing finite element methods. Computational simulation is also employed to model fluid dynamics. However, computation fluid dynamic (CFD) tools are not as widely applied in the design process as either CAD or structural analysis tools due, in part, to the long set-up times and high costs (both human and computational) associated with complex fluid flow.[4]

The conventional steps for CFD, structural analysis, and other disciplines in the design process are: 1) surface generation, 2) mesh generation, 3) obtaining a solution, and 4) post-processing visualization. Surfaces of the domain to be analyzed (e.g., a turbine blade passage) are generated from a CAD system. These surfaces are used to create a domain (i.e., a closed volume) of interest which is discretized in one of many different manners to form a mesh. The mesh, along with boundary information, is used by a numerical solver to obtain a solution to the governing equations over the entire volume. This solution and mesh are then displayed graphically, allowing the user to examine the results and extract the data needed to understand the domain physics. This process is illustrated in Fig. 1. Data are transmitted between these steps via files; for example, output from a CAD system might be in the form of IGES file(s), which are read by the mesh generator. Similarly, the mesh generator, solvers and visualization tools would each generate output and read input in a variety of formats.

Mesh generation has long been recognized as a bottleneck in the CFD process.[5] While much research on automating the volume mesh generation process have been relatively successful, these methods rely on appropriate initial surface triangulation to work properly. Surface discretization has been one of the least automated steps in computational simulation due to its dependence on implicitly defined CAD surfaces and curves. Differences in CAD geometry engines manifest themselves in discrepancies in their interpretation of the same entities. This lack of "good" geometry causes significant problems for mesh generators, requiring users to "repair" the CAD geometry before mesh generation. The problem is exacerbated when CAD geometry is translated to other forms (e.g., IGES) which do not include important topological and construction information in addition to entity geometry.[6]

One technique to avoid these problems is to access the CAD geometry directly from the mesh generating software, rather than through files. By accessing the geometry model (not a discretized version) in its native environment, this approach avoids translation to a format which can deplete the model of topological information.[6]

Our approach to enable models developed in the Denali software environment to directly access CAD geometry and functions is through an Application Programming Interface (API) known as CAPRI.[7] CAPRI provides a layer of indirection through which CAD-specific data may be accessed by an application program using CAD-system neutral C and FORTRAN language function calls. CAPRI supports a general set of CAD operations such as truth testing, geometry construction and entity queries.

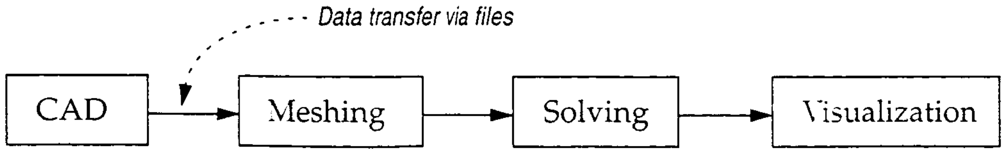

Figure 1: Conventional Analysis Process (Ref. [7])

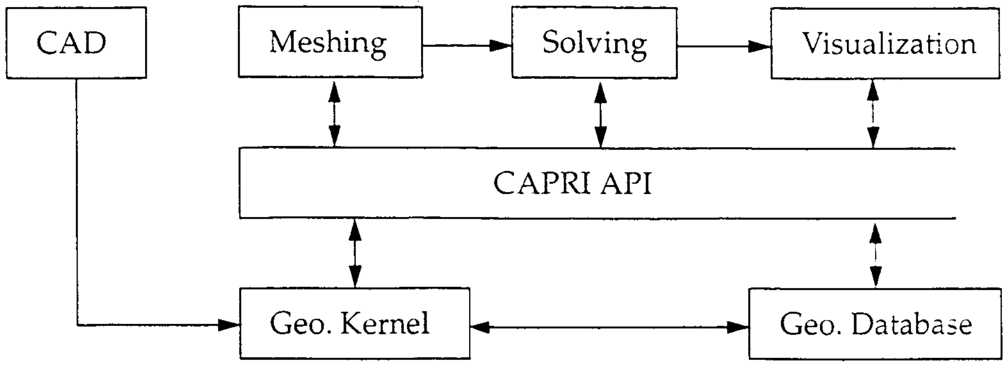

Figure 2: CAPRI-based Analysis Process (Ref. [7])

CAPRI isolates the top level applications (mesh generators, solvers, and visualization programs) from the geometry engine (see Fig. 2). It also allows the replacement of one geometry kernel with another, without affecting the top-level application. Additionally, CAPRI allows non-geometry information, such as material or condition information (e.g., temperature) to be attached to the geometry entities.

A geometry-centric approach, such as the one supported by CAPRI, is vital to foster concurrent engineering, especially in multidisciplinary aerospace design. This approach allows requisite information, both geometric and non-geometric, to be captured and used in the design process. For example, a CFD solver, using the supplied mesh, would generate a solution consisting of fluid properties (e.g., temperature, pressure, etc.) for each volume. This data is attached to appropriate mesh volumes through CAPRI, and accessed by other applications through context-specific *views* of the CAPRI data. For example, a CFD visualization application program would obtain the geometry directly (through CAPRI) from the CAD geometry kernel while the CFD data would be supplied from CAPRI attachments.

Implementation Details: Overview

We have designed and implemented a basic object-oriented architecture to allow both Denali models and external application programs to access geometry data through the CAPRI API. Figure 3 illustrates a simplified view of the architecture participants. The designer directs the Client, which is either a Denali model or external application program, to generate a mesh for a specific CAD part. The MeshGenerator is responsible for generating an appropriate mesh given a CAD part, and is done in conjunction with the CAPRI middleware and a CAD geometry kernel (such as UniGraphics Parasolid). The generated mesh is returned to the Client and passed to the Analysis Controller (it may also be viewed at this time by a visualization tool). The Analysis Controller uses the mesh to perform an engineering analysis, such as CFD. At the end of each time-step or the end of the analysis, CFD data is attached to geometry via calls to CAPRI. The mesh, attached CFD information, and geometry boundary surfaces data are retrieved by a Visualizer which displays the simulation results to the designer.

Mesh Generation

A general class structure has been developed to frame the mesh generation process using CAPRI (see Fig. 4). The MeshGeneratorMgr class provides a single access point (implemented as a Singleton object) for clients to obtain a mesh from a CAD part. There are many different techniques for generating a mesh, so Denali allows users to specify a particular mesh generation technique as implemented by a Java class. These different classes can be dynamically plugged into the Denali framework so long as they subclass the abstract MeshGenerator class. In Fig. 4, the MeshGenerator class has been subclassed by the DenaliMeshGenerator class, which defines concrete implementations of MeshGenerator abstract methods (indicated by italics). MeshGenerator subclass' can use whatever means they wish to generate a mesh; this allows the use of existing IGES- and STEP-based tools. In our research we have written a simple Java mesh

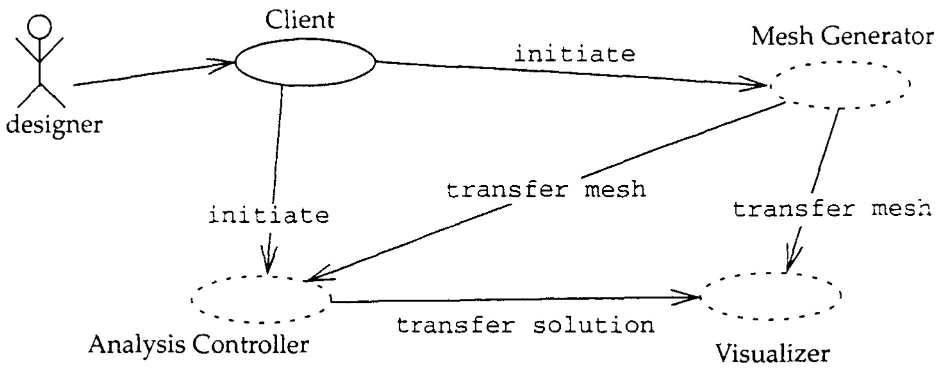

Figure 3: Global view of architecture

generator based on constrained Delaunay triangulation. The generator, which is implemented in the DenaliMeshGenerator class, utilizes CAPRI to access native CAD geometry and generate a mesh. The Capri class is a Java wrapper which duplicates the CAPRI API function call list and accesses the CAPRI C-language function calls through the Java Native Interface (JNI).

Using CAPRI, the DenaiMeshGenerator loads a CAD part, then retrieves a list of volumes from CAPRI. For each volume, CAPRI returns a simplical decomposition of each of the CAD face entities. Each of these triangulations are manifold with respect to their CAD edges. Typically, the triangulation is irregular and planar regions are decomposed into as few triangles as possible. A new mesh with higher quality is constructed by creating additional triangles using points on CAD faces obtained from CAPRI.

Since it was not our intent to write a robust and guaranteed-quality mesh generation tool, we developed the Delaunay triangulation mesh generator only to the point to demonstrate access to geometry through CAPRI. In the future, we may choose to continue this work and improve upon it using the work of Ruppert[9], Chew[10] and Aftosmis.[11].

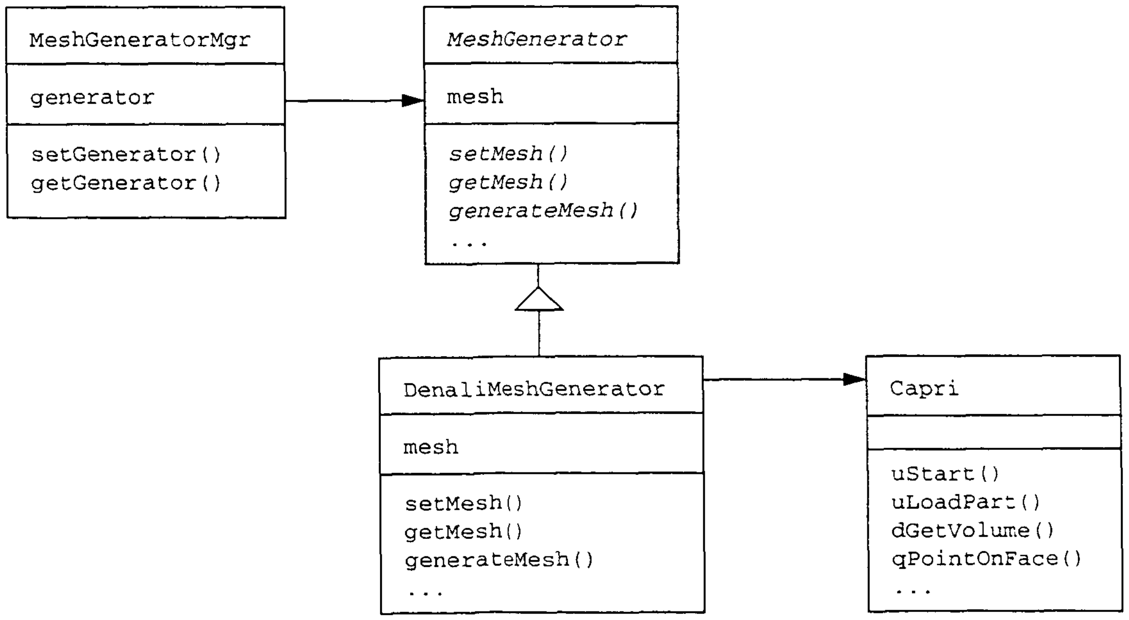

Figure 4: Mesh generation class structure

Visualization

As indicated above, visualization tools are essential to view solver solutions overlaid on geometry and mesh data. One visualization tool, called the *Geometry Viewer,* is a stand-alone visual interface and debugging aid provided with CAPRI. It is similar to the *Visual3* program[12] used for scientific visualization, but is limited to viewing meshes and geometry. We have loosely integrated the Geometry Viewer within the Denali framework so as to demonstrate the ability to visualize geometry and mesh using the CAPRI library.

One of the goals of the Denali framework was to provide a platform-independent system for aerospace design. Towards that end we have endeavored to use Java™ as much as possible in developing the framework. However, in some cases, no Java-based tool were available; this is currently the case with visualization tools. It is sometimes possible to partition the non-Java software into a client-server architecture with the non-Java software located on a centralized machine made accessible via RMI or CORBA. However, it appears that this is not currently possible with existing visualization tools. Consequently we are exploring the possibility of developing a visualization tool similar to *Visual3* or the *Geometry Viewer* using Java, and in particular, the Java3D API.[13] Alternatively, we will have to require users to install platform-specific visualization tools on each desktop using Denali in order to view geometry and/or simulation solutions.

Plans for Year 3

- The majority of work in year 3 will focus on the development of aircraft models for use in Denali. In anticipation of the year 3 work, we have licensed the Base of Aircraft Data (BADA) from the Eurocontrol Experimental Centre (EEC). The Base of Aircraft Data (BADA) provides a set of ASCII files containing performance and operating procedure coefficients for 186 different aircraft types. The coefficients include those used to calculate thrust, drag and fuel flow and those used to specify nominal cruise, climb and descent speeds.
- We will continue to work on implementing a database management system based on the Java Data Objects (JDO) specification.[8] The final JDO specification is expected to be released soon, and we will be evaluating different implementations of the specification to see which is best for supporting Denali.
- We will also be working on integrating more robust grid generator and visualization tools which utilize the CAPRI interface.

References

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APPENDIX B: Publications

Conference Publications

1. Lin, Risheng and Afjeh, A. A., "An Extensible, Interchangeable and Sharable Database Model for Improving Multidisciplinary Aircraft Design," AIAA 2002- 5613, 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, 4 - 6 September 2002, Atlanta, Georgia.

2. Lin, Risheng and Afjeh, A. A., "Interactive, Secure Web-enabled Aircraft Engine Simulation Using XML Databinding Integration," AIAA 2002- 4058, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 7 - 10 July 2002, Indianapolis, Indiana.

Journal Articles

3. Reed, J. A., Follen, G. J., and Afjeh, A. A., "Improving the aircraft design process using Web-based modeling and simulation, "ACM Transactions on Modeling and Computer Simulation, Vol. 10, No. 1, 2000, pp. 58-83, (special issue on Web-based Modeling and Simulation).

4. Lin, Risheng and Afjeh, A. A., "On XML-based Integrated Database Model for Multidisciplinary Aircraft Design," AIAA Journal of Aerospace Computing, Information, and Communication, To appear in 2004.

AIAA

AIAA 2002- 5613

An Extensible, Interchangeable and Sharable Database Model for Improving Multidisciplinary Aircraft Design

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9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization
4 - 6 September 2002
Atlanta, Georgia

AIAA-2002-5613

AN EXTENSIBLE, INTERCHANGEABLE AND SHARABLE DATABASE MODEL FOR IMPROVING MULTIDISCIPLINARY AIRCRAFT DESIGN

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ABSTRACT

Advances in computer capacity and speed together with increasing demands on efficiency of aircraft design process have intensified the use of simulation-based analysis tools to explore design alternatives both at the component and system levels. High fidelity engineering simulation, typically needed for aircraft design, will require extensive computational resources and database support for the purposes of design optimization as many disciplines are necessarily involved. Even relatively simplified models require exchange of large amounts of data among various disciplinary analyses. Crucial to an efficient aircraft simulation-based design therefore is a robust data modeling methodology for both recording the information and providing data transfer readily and reliably. To meet this goal, data modeling issues involved in the aircraft multidisciplinary design are first analyzed in this study. Next, an XML-based, extensible data object model for multidisciplinary aircraft design is constructed and implemented. The implementation of the model through aircraft databinding allows the design applications to access and manipulate any disciplinary data with a lightweight and easy-to-use API. In addition, language independent representation of aircraft disciplinary data in the model fosters interoperability amongst heterogeneous systems thereby facilitating data sharing and exchange between various design tools and systems.

INTRODUCTION

Improvement in aircraft design involves research into many distinct disciplines: aerodynamics, structures, propulsion, noise, controls, and others. Due to the inherent complexity and coupling of the disciplinary design issues, simulation-based analyses of aircraft design will naturally evolve to complex assemblies of dynamically interacting disciplines where each of the disciplines interacts to various degrees with the other disciplines (Figure1). The multidisciplinary couplings inherent in aircraft design not only increase computational burden but also present additional challenges beyond those encountered in a single-disciplinary simulation of aircraft. The increased computational burden simply reflects the massive size of the problem, with enormous amounts of analysis data and design variables adding up with each additional discipline. As a result, designing and implementing a new simulation methodology that supports the multidisciplinary aircraft design process can be an impractically expensive and time-intensive task. Currently reasonably well-developed and validated software tools exist within individual disciplines. Hence, a key requirement for the success of a practical multidisciplinary aircraft simulation is to provide the tools necessary to support efficient integration of these computer simulation codes. This approach demands a well-constructed data sharing and validation environment, which includes a robust data modeling and/or the use of a data exchange standard.

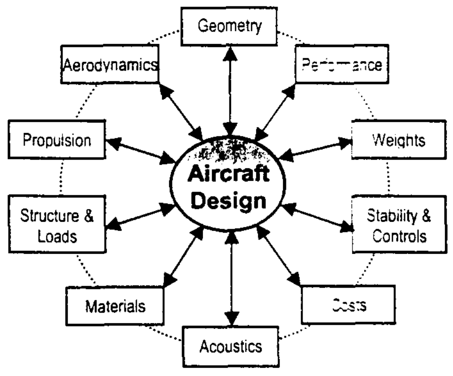

Figure1. Typical disciplines in an aircraft design

Traditional preliminary design procedures often decompose the aircraft into isolated components (wing, fuselage, engine, etc.) and focus attention on the individual disciplines (geometry, propulsion, acoustics, etc.). The common approach is to perform disciplinary analysis in a sequential manner where one discipline may synthesize the results of the preceding analysis

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during the simulation run-time. The current practice emphasizes the multidisciplinary nature of the design of an aircraft through the use of integrated product teams. However, integrated and sharable aircraft design databases are not yet common in industry. One reason for this is because aircraft system simulation typically requires complex numerical algorithms and coupling models between dominant disciplines. Accordingly, developers can barely afford to build propriety data storage models around successful design applications. With the distinction, each discipline focuses on activities related to its own concerns. The designers typically provide each discipline with only those data which are required in performing the specific task of that discipline, and often, they spend 50-80% of their time organizing data and moving it between applications [1]. A very common problem with this kind of data exchange is data consistency. It is not uncommon to find that during the design phase, a particular discipline's updated calculations have not been effectively communicated with other disciplines involved in the design effort. This breakdown in the data exchange process results in inconsistent predictions among the various disciplines and could cause, for example, an "optimal" aerodynamic design that can not contain a sufficient supportive structure.

Other factors that can make the design process less efficient are data redundancy and the lack of a standard data format. To synthesize and evaluate aircraft designs, numerous software packages for analysis, post processing or data visualization are often employed. Because the aircraft simulation computing environments are typically heterogeneous, with platforms ranging from personal computers to UNIX workstations, to supercomputers, their internal data representations are normally not the same, these tools in general use different, possibly proprietary, data formats. Moreover, data are often duplicated in a slightly different format for the various disciplines' use. This lack of portability of data in different file systems greatly hinders sharing and exchanging of interdisciplinary data. In addition, the multiplicity of representation of disciplinary datasets not only wastes storage media capacity and CPU time, but it also generates an enormous overhead in terms of data translator development, additional software and data management. Although in some cases, custom translation tools are available to "massage" the data into the appropriate format; users still spend considerable time and effort tracking and validating data. As the analysis and design tasks become more distributed, communications requirements become more severe. Advances in aircraft disciplinary analyses and the growing trend in the use of high fidelity models in the last two decades have only aggravated these problems, increasing the amount of shared information and outpacing developments in interdisciplinary communications and system design methods [2].

Improving the simulation-based aircraft design process, therefore, requires the development of an integrated software environment which can provide interoperability standards so that information can flow seamlessly across heterogeneous machines, computing platforms, programming languages, and data and process representations [3]. In particular, emphasis should be placed on the generation of a database management system specifically crafted to facilitate multidisciplinary aircraft design. The subject of this paper is to provide a sharable and interchangeable database model for multidisciplinary aircraft design, with the intent to promote the interdisciplinary information sharing.

DESIGN REQUIREMENTS

The Multidisciplinary Optimization Branch (MDOB) at NASA Langley Research Center (LaRC) recently investigated frameworks for supporting multidisciplinary analysis and optimization research. The major goals of this program were to develop the interactions among disciplines and promote sharing of information. This section outlines several design requirements related to the data modeling that are particularly evident in the aircraft multidisciplinary analysis and optimization, based on the experience gained from the Framework for Multidisciplinary Design Optimization (MDO) project [4,5].

1) *Standards.* Use of standards in a database model preserves investment, results in lower maintenance costs and also promotes information sharing. It ensures that there are no interoperability problems between design teams that use the open standard.
2) *Sharable.* Data must be shared between disciplines and within disciplines with all the applicable quality, consistency and integrity checks [1]. Information sharing can reduce discipline isolation and encourage the use of the most advanced techniques while increasing the awareness of the effects each discipline has upon other disciplines and for reduced design cycle time [6].
3) *High-level interface.* Database model should allow the user to use and modify aircraft data in complex MDO problem formulations easily without low-level programming. By raising the level of abstraction at which the user programs the MDO problems, they could be constructed faster and be less prone to error.
4) *Extensible.* Advances in aircraft design will have new disciplines to appear, such as maintainability, productivity, etc., therefore database model should

be extensible and should provide support for developing the interfaces required to integrate new disciplinary information into the system easily. As a result, the user would avoid having to wait for the needed features to appear in new releases.

5) *Large data size.* Since aircraft design involves a lot of disciplinary analysis variables, database model should be able to handle large problem sizes. Supporting techniques should allow database to grow and shrink dynamically, but do not degrade the database performance dramatically.
6) *Object-oriented.* Database model should be designed using object-oriented principles. Object-oriented design [7] has several advantages in aircraft design. For example, object-oriented principles provide *polymorphism* for analysis or optimization methods at run time. Object-oriented software design has been employed as a tool in providing a flexible, extensible, and robust multidisciplinary toolkit that establishes the protocol for interfacing optimization with computationally-intensive simulations [8].
7) *Distributed.* For large problems, the designers in different disciplinary teams need to be able to conveniently work together by *collaborative design* [9]. It is desirable that a database model could support disciplinary code execution distributed across a network of heterogeneous computers.

The implementation of a database to meet all these requirements is a major challenge. In the following sections, we focus on the design and development of a XML-based database model as a first step toward meeting that challenge.

XML FOR AIRCRAFT DATA

XML [10] is a generic, robust syntax for developing specialized markup language, which adds identifiers, or tags, to certain data so that they may be recognized and acted upon during future processing. Several good features inherent within XML would make it well suited to the task for satisfying multidisciplinary data requirements.

As indicated in the Design Requirements section, data sharing is an essential element in preventing design isolation between various aircraft disciplinary components. XML provides a hierarchical container that is platform-, language-, and vendor-independent and separates the content from any environment that may process it. It is normatively tied to an existing ISO standard, ISO 8879 (SGML) [11], and is an acceptable candidate for full use within other ISO standards without the need for further standardization effort. By accepting and sending aircraft data in plain text format, the requirement to have a standard binary encoding or storage format is eliminated, allowing aircraft applications running on disparate platforms to readily communicate with each other. Aircraft design applications written in any other programming language that process XML can be reused on any tier in a multi-tiered client/server environment or distributed computing, offering an added level of reuse for aircraft data. The same cannot be said of any previous platform-specific binary executables. Because XML is or will be fully supported in Web browsers, it should be possible to use Web technology to communicate disciplinary data entities in a collaborative aircraft design environment.

When using XML, it not only allows input of the data, but also permits one to define the structural relationships that exist inside the data. The hierarchical structure in XML combined with its linking capabilities [12, 13] can encode a wide variety of aircraft data structures. The element's name, attributes and content model are closely related to data class name, properties and composition associations in object-oriented aircraft simulation. By using XML to represent aircraft data, it is possible to faithfully model any structural aircraft data of a chosen component in their design context.

In traditional aircraft multidisciplinary analyses, validating data format and ensuring content correctness is another major hurdles in achieving data exchanges of aircraft data. XML also provides facilities for the syntactic validation of documents against formal rules. This can be achieved through Document Type Declaration (DTD) [10] or XML-Schema [14], which defines the constraints and logical structures that an XML document should be constructed. A data file written in XML is considered valid when it follows the constraints that the DTD or XML-Schema lays out for the structures of XML data. XML Schema also offers a number of other significant advantages over DTD, such as more advanced data types and a very elaborate content model. Without XML, any validation of aircraft data has to be implemented at the expense of work by application developers. When using XML to encode aircraft design data, XML parser can be used readily to check the validity and integrity of the aircraft data stored in XML documents. This guarantees the data producer and consumer exchange the aircraft design data correctly.

The various advantages outlined above present compelling reasons to use XML for aircraft design data representation. However, the solution is not as easy as it might at first appear. While XML is a useful technology, it is, ultimately, simply serialization syntax. In particular, just putting aircraft data into XML form does not make it any more interchangeable than it was before, because the recipient of the data must still have an understanding of what the design-specific data are inside XML file *semantically* in order to process them correctly. Semantic interoperability is of vital importance between different aircraft disciplines and simulation components, as it enables them to agree on how to use aircraft data and how to interpret application data for different disciplinary designs. In addition, there are still several other requirements (for example, large datasets, object-oriented, high-level interface, etc.) to meet in order to use XML to communicate aircraft design data between disciplines efficiently.

In the next section, we will provide the design of an extensible aircraft data object model. This model will be used to interpret aircraft design data between design disciplines, and serve as a foundation to implement a XML-based aircraft database to meet all the design requirements.

DATA OBJECT MODEL

The aircraft design process [15] can be divided into three phases: *conceptual design*, *preliminary design*, and *detailed design*. Since aircraft design by its nature is a very complicated process and involves vast amounts of data, for the purposes of this paper, we will only demonstrate the data model in the aircraft conceptual design. Conceptual design involves the exploration of alternate concepts for satisfying aircraft design requirements. Trade-off studies between aircraft conceptual designs are made with system synthesis tools, which encompass most of aircraft components and a broad range of disciplinary interactions.

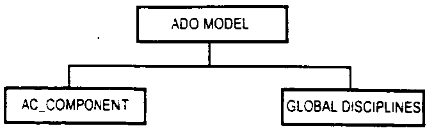
In order to effectively represent aircraft design data using XML, a set of data object structures was first designed. Figure 2 shows an overall layout of a simplified data model. The designed database model is composed of aircraft components and other disciplinary data objects (Fig. 2a). The overall model is organized in a strict hierarchical manner in accordance with the XML topology. Each node in the data structure shown here is represented as an *Aircraft Data Object* (ADO). These objects hold no complex design logic, but they contain typed data and preserve the logical structure of the model. The ADO model precisely defines the intellectual content of aircraft-related data, including the organizational structure supporting such data and the conventions adopted to standardize the data exchange process. The functional model identifies a common process in order to ascertain what data are required for a typical aircraft design process. Figure 2 also indicates (informally) what data, if any, are encapsulated within each node object.

Aircraft Components

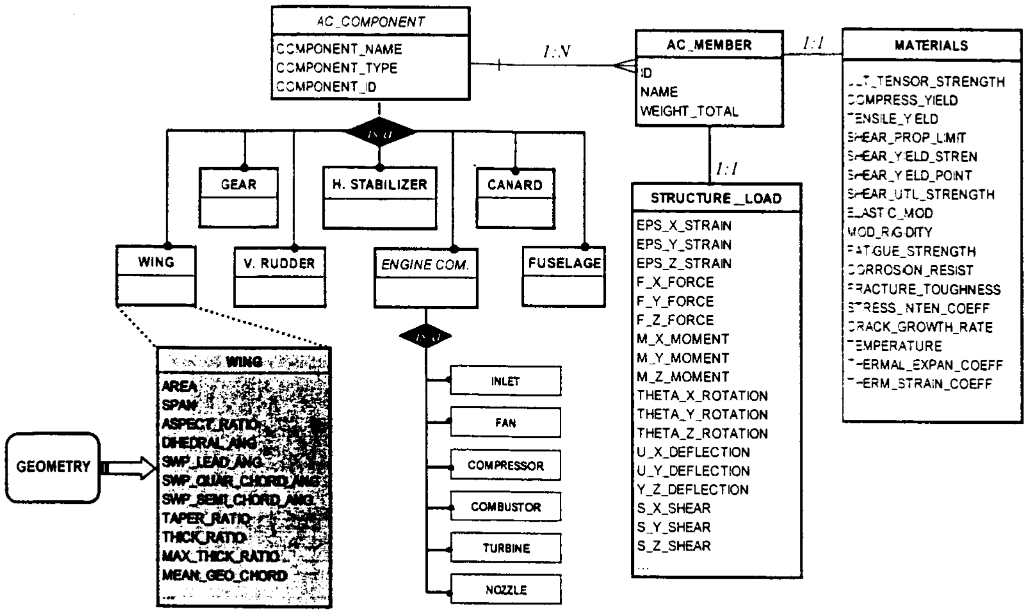
An aircraft component (*AC_Component*) object can be an engine, fuselage, landing gear, canard, horizontal stabilizer, vertical rudder, or wing (Figure 2b). Every component has a user-defined name and unique *component type*, which characterizes the nature of its usage. For practical purposes, a component type is characterized as a set of possible values, such as WING, ENGINE, etc. There is a special data type, called *object identification (Component_ID)*, whose value is the unique identifiers of encapsulated objects to be referenced in the aircraft design.

Each aircraft component itself may be made up of physically distinguishable *subcomponents* or *parts*. For example, an engine is made up of inlet, fan, compressor, combustor, turbine and nozzle subcomponents. Likewise, most landing gears have parts like wheel, tire, brake assembly, etc. Every subcomponent is represented by a data object, with member properties and subtypes (not shown here for simplicity) encapsulated in it. Each part is modeled as a *component member* object and encapsulated as a child in *AC_Component*. An important feature to note from Figure 2b is the local inclusion of several disciplinary data. Since each member object has its own materials requirements (e.g., modulus of rigidity, fatigue strength, etc), structure and loads characteristics (e.g., strain, stress, displacement, etc), these disciplinary data are naturally considered as parts of a member object. The local inclusion of component disciplines prevents design data isolation, and promotes data sharing and exchange during the design process. Aircraft propulsion system (not shown here) is considered as a member type for the engine components. A more detailed demonstration for aircraft propulsion model can be found in Ref. [16].

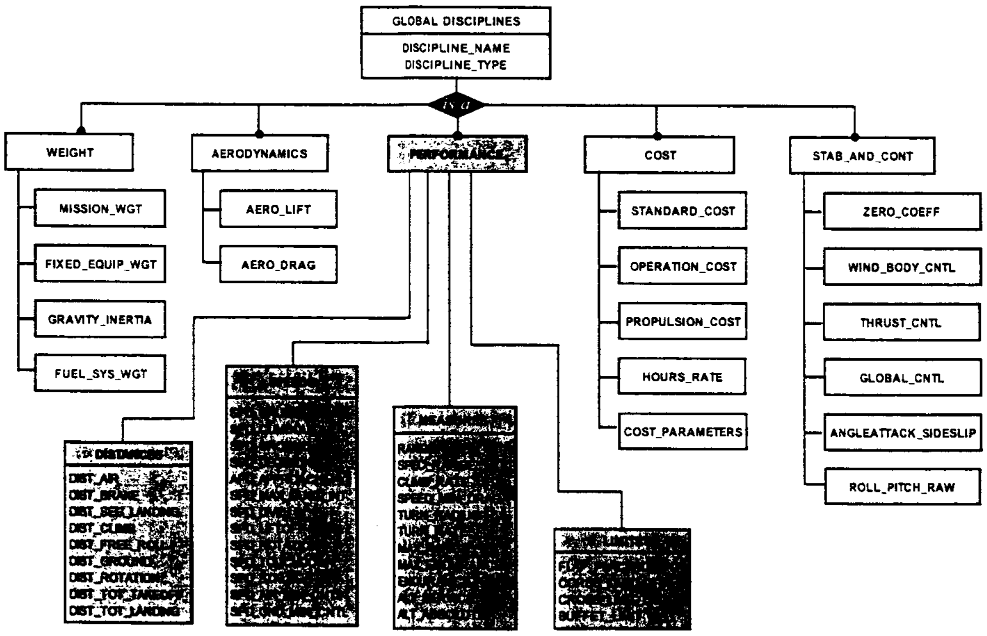
Besides the hierarchical layer of the data objects structure, the designed model also encourages the use of data object *abstraction*, *inheritance*, and *composition*. Returning to Figure 2b, we can see that each of the specific aircraft components is patterned as an "*is/a*" relationship with *AC_Component*, therefore each specific component data model automatically inherits all the data member proprieties and subtypes (materials, structure and load) of its parent. In this sense, *AC_Component* provides a data abstraction for all its component children, allowing each single element to be treated the same way as the assemblies of elements in its internal data representation. For each specific aircraft component data modeling, we can represent the hierarchical structure of the data properties, substructure and their disciplinary data using *recursive composition*. For example, we can combine multiple sets of rotor and stator blade data objects to form a fan component data. This technique allows us to build increasingly complex aircraft data components out of simple data object models. The designed database model gives us a convenient way to construct and use arbitrary complex aircraft data model and makes the



(a) Top level children of ADO model



(b) Aircraft components data object model



(c) GlobalDisciplines data object model

Figure 2. Aircraft data object model

model totally extensible for future enhancements.

Geometry Modeling

Component geometry modeling is somewhat unique in aircraft design. All disciplines share the same geometry. Strong interactions between the disciplines are very common and complicated. For example, during operation, the geometry of a flexible structure (e.g., wing) may change due to the aeroelastic effects. Geometry modeling must, therefore, be accurate and suitable for various disciplines (e.g. deflection and load). For a multidisciplinary optimization problem, the application must also use a consistent parameterization across all disciplines. Thus, an application requires a common geometry dataset that can be manipulated and shared among various disciplines [17].

STEP Application Protocol *AP 203* — Configuration Controlled 3D Designs of Mechanical Parts and Assemblies [18] — is a set of standards that defines the CAD geometry, topology, and configuration management data of solid models for mechanical parts. AP203 supports wireframe, surfaces, solids, configuration management, and assemblies. The STEP modelers have undertaken the very difficult job of defining mappings between the different representations of the same information. For example, a curve on the surface of fuselage can be represented as a B-spline, as a list of curve segments, or as NURBs. In our aircraft database, a placeholder has been designed to support various aircraft components' geometry disciplinary data that conform to the STEP-based model. Because different components normally have very different geometry requirements, the geometry disciplinary data are considered local to every concrete component. Different fidelity geometry models can be chosen for use in the design process.

Global Disciplines

Other disciplinary data, such as stability and control, aerodynamic, performance, cost, and weight data, are currently modeled as *global* objects (and grouped together as *GlobalDisciplines*) of the aircraft database (Figure 2c). This seems a little unnatural, however, these calculations have been traditionally grouped by discipline in aircraft design, and they probably will continue to be associated in this manner for some time to come. The relationship between these disciplinary data and aircraft database is also modeled as parent to child. For example, one of the relative important design parameters on the conceptual vehicle design is system performance. This disciplinary category in our design is currently made up of different criteria data objects, such as *distance, speeds, limits, measures,* etc., as shown in Figure 2c. The figure also gives the sample data that may be included in the discipline. New data will be added in as the data object model evolves in the future.

SCHEMA DESIGN

Aircraft Schema establishes a bridge between XML-based description of aircraft data and the ADO model. A set of aircraft Schema has been designed in XML Schema language that specifies how the constituents of the ADO object are mapped to an underlying XML structure. It associates each piece of information defined in ADO to a precise location in the XML structure.

Each aircraft data object defined in ADO is mapped to one or more nodes. For the most part, the aircraft Schema closely follows the ADO model. Aircraft-schema file must be ADO-compliant in order for other applications to be able to properly interpret aircraft data. This is particularly important when trying to transfer data between different disciplines and different storage models, as there must be agreed-upon data structure and syntax for different systems to understand each other. The rules in ADO model will guarantee that the schema description of aircraft data is syntactically correct and follows the grammar defined within it. An important feature of the ADO data model is the hierarchical structure, which allows the aircraft data file to be structured as a rooted directed graph, so it is necessary to map the directed graph of aircraft data in XML onto a tree of aircraft data objects specified in ADO. However, when a given piece of information is listed as being "under" a node, there are actually two possibilities: the information can be stored as data in the current node, or it can be stored as data under a separate child node. The aircraft schema also determines which of these two possibilities are best for each situation.

An example of aircraft schema design is demonstrated in Figure 3. Based on the ADO model, an aircraft database model includes several kinds of component data objects (such as Wing, Fuselage etc.), which can be contained in an aircraft, and a *GobalDisciplines* data object. To create aircraft component constructs, we start by creating a basic aircraft component complex type, `AircraftComponent_t`, which contains a single `AircraftMember` element. An `AircraftMember` is constrained by its complexType `AircraftMember_t`, where `AircraftMember_t` itself contains `Name` `TotalWeight`, `Materials`, and `StructureLoad` elements, and in turn, are constrained by their corresponding built-in string type, double type and similarly-defined complexTypes separately.

An aircraft component also contains a set of desired data attributes – componentType, name, identification – that are encapsulated in the *AircraftComponent* object.

```
<?xml version="1.0"?>
<xsd:schema  targetNamespace="http://mems1.ni.utoledo.edu/aircraft"
      xmlns="http://mems1.ni.utoledo.edu/aircraft"
      xmlns:xsd="http://www.w3.org/2001/XMLSchema"
      elementFormDefault="qualified">

     <xsd:include schemaLocation="materials.xsd" />
     <xsd:include schemaLocation="structureload.xsd"  >
     <xsd:include schemaLocation="globaldisciplines.xsd" />
     <!-- other basic schema components are included here-->

      <xsd:complexType name="AircraftComponent_t">
            <xsd:sequence>
                  <xsd:element name="AircraftMember" type="AircraftMember_t"
                     maxOccurs="unbounded"/>
            </xsd:sequence>
            <xsd:attributeGroup ref="ComponentAttributes"/>
      </xsd:complexType>

      <xsd:attributeGroup name="ComponentAttributes">
         <xsd:attribute name="componentType" use="required">
            <xsd:simpleType>
                <xsd:restriction base="xsd:string">
                   <xsd:enumeration value="WING"/>
                   <xsd:enumeration value="LANDINGGEAR"/>
                    <!-- other aircraft types are continued here-->
                </xsd:restriction>
            </xsd:simpleType>
         </xsd:attribute>
         <xsd:attribute name="name" type="xsd:string" use="required"/>
         <xsd:attribute name="idetification" type="xsd:ID" use="required"/>
       </xsd:attributeGroup>

      <xsd:complexType name=" AircraftMember _t">
            <xsd:sequence>
                <xsd:element name="Name" type="xsd:string" />
                <xsd:element name="TotalWeight" type="xsd:double" />
                 <xsd:element name="Materials" type="Materials_t" />
                <xsd:element name="StructureLoad" type="StructureLoad_t" />
            </xsd:sequence>
            <xsd:attribute name="memberID" type="xsd:ID"/>
      </xsd:complexType>

      <xsd:complexType name="Wing_t">
            <xsd:complexContent>
                  <xsd:extension base="AircraftComponent_t">
                        <xsd:sequence>
                              <xsd:element name="Area" type="xsd:string"/>
                              <xsd:element name="Span" type="xsd:string"/>
                              <!-- other geometry data are continued here-->
                        </xsd:sequence>
                  </xsd:extension>
            </xsd:complexContent>
      </xsd:complexType>

       <xsd:element name="Aircraft">
         <xsd:complexType>
            <xsd:sequence>
                  <xsd:element name="Wing" type="Wing_t" " minOccurs="2"
                                  maxOccurs="2"/>
                  <!-- other aircraft components are defined here  -->
                  <xsd:element name="GlobalDisciplines"
                                  type="GlobalDisciplines_t"/>
            </xsd:sequence>
         </xsd:complexType>
       </xsd:element>
</xsd:schema>
```

Figure 3. A sample aircraft schema

These attributes are grouped together, represented by `ComponentAttributes`, and referenced by name in the *AircraftComponent*'s complexType declaration. For example, the `componentType` attribute is restricted to a set of predefined type values, such as `WING`, `LANDINGGEAR`, etc, these types are constrained by enumerations definition in the simpleType definition.

Then a set of concrete aircraft components is built based on the `AircraftComponent_t` complexType. The technique here is to derive new (complex) aircraft component types by extending an existing type. For example, when building data schema for the wing component, we define the content model for Wing element using new complex types, `Wing_t`, in the usual way; in addition, we indicate that the concrete wing component (Wing) is extending the `AircraftComponent_t` base type. When a complex type is derived by extension, its effective content model is the content model of the *base* type plus the content model specified in the type derivation. In the case of `Wing` element, its content model `Wing_t` is the content model of *AircraftComponent* plus the declarations for the wing's local data elements and attributes.

Other aircraft component and disciplinary data schema can be designed in a similar manner. Finally, the whole aircraft schema is composed of different aircraft components and *GlobalDisciplines* data. Note that when designing aircraft schema, all the basic components and disciplinary schemas do not need to be coded in a single file during the design time. For example, Figure 3 does not explicitly show the disciplinary schema such as material, structure and load, components other than wing, etc. instead, it uses '`include`' element to indicate that these schemas exist outside the aircraft schema file. In this way, each schema can be designed separately by different disciplinary groups, and then "included" together during the run time. This kind of flexible design will allow for modular development and easy modification of aircraft schema as its data object model evolves in the future.

Because of the important nature of aircraft geometry disciplinary data, our database model currently uses STEP AP203 standard to encode all the aircraft geometry data. STEP models are written using the EXPRESS language [19]. EXPRESS provides a rich collection of types and inheritance organizations to capture data structure and to describe information requirements and correctness conditions necessary for meaningful data exchange, therefore makes it easier to describe an accurate aircraft geometry model. However EXPRESS does not dictate how the models should be implemented using various database technologies. Implementers must convert an EXPRESS information model into schema definitions for the target database. This conversion requires a mapping from the EXPRESS language into the data model of the target database system. EXPRESS information models describe logical structures that must be mapped to a software technology before they can be used.

Given an EXPRESS schema that specifies aircraft geometry information, it is possible to define a set of schema languages (such as DTD or XML-Schema) that are used to encode geometry information specified in EXPRESS schema. Several researches have been done to encode EXPRESS schema by DTDs, among which the most important one is STEP Part 28 (XML representation of EXPRESS-driven data) [20], which includes a set of standard DTD declarations to represent any EXPRESS schemas in XML as well as data corresponding to an EXPRESS schema. Therefore, it is convenient to take advantage of this standard to encode all aircraft geometry data. This is done by designing a STEP CAD Conventer, which can convert from a valid aircraft geometry STEP model constrained by DTD to XML-Schema. In this way, the general schema design techniques provided in this section can still be applied to aircraft geometry data. Moreover, by using XML-Schema to represent STEP CAD model, it can benefit the good features in XML-Schema, such as modular schema inclusion (xinclude), and also offer a uniform data schema formalism for database implementation. A simple illustration is given in Figure 4.

```
<!—DTD for 3D point-->
<!ELEMENT Cartesian_point EMPTY>
<!ATTLIST Cartesian_point
      x-id ID #REQUIRED
      X CDATA #REQUIRED
      Y CDATA #REQUIRED
      Z CDATA #REQUIRED
>

<!—XML Schema for 3D-point after conversion-->
<xsd:schema xmlns:xsd="http://www.w3.org/2001/XMLSchema">
      <xsd:element name="Cartesian_point">
            <xsd:complexType>
                  <xsd:attribute name="X" type="xsd:string" use="required"/>
                  <xsd:attribute name="Z" type="xsd:string" use="required"/>
                  <xsd:attribute name="Y" type="xsd:string" use="required"/>
                  <xsd:attribute name="x-id" type="xsd:ID" use="required"/>
            </xsd:complexType>
      </xsd:element>
</xsd:schema>
```

Figure 4. Example STEP CAD Converter for 3D point

AIRCRAFT DATABINDING

Multidisciplinary design of aircraft systems is a complex, computationally intensive process that combines discipline analyses with intensive data exchange and decision making. The decision making is based on the overall design optimization but is greatly assisted by data sharing and automation [5]. Aircraft data encoded by XML provides a means to share disciplinary data between aircraft design teams, but their physical storage form on the external storage medium is still not intelligible or easily accessible. *Aircraft databinding* provides an implementation for the designed data object model. Meanwhile, it also encapsulates a convenient way for conversion between the aircraft data in XML file and their object representations *automatically* and provides a lightweight and easy-to-use API, which facilities the design applications to access, modify and store any aircraft data object using a high-level object interface.

Aircraft Databinding includes two components: an *aircraft schema compiler* and a *marshalling framework*. It was written in Java; thus the software can be run on different design platforms.

Schema Compiler

The *aircraft schema compiler* is designed to automatically translate the aircraft schema into a set of derived aircraft data class source codes. It maps instances of aircraft schemas into their data object models, and then generates a set of classes and types to represent those models (Figure 5).

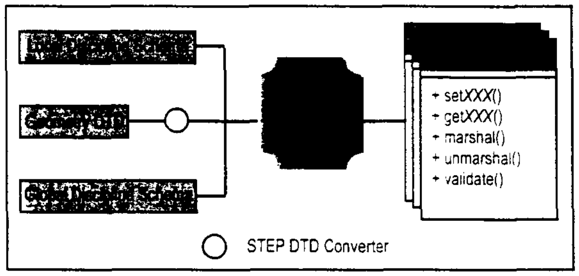


Figure 5. Schema compiler in Aircraft databinding

Let's consider how the data class is generated by schema compiler with input of the schema defined in previous section. With the "Aircraft" schema defined, attributes represent simple Java types, usually primitives. Thus, *name* and *componentType* attributes in the *AircraftComponent*'s complexType are compiled into Java type of String, and *identification* attribute becomes Java primitive of type *int*, respectively. All elements (along with its type information which specifies the content model), such as *Aircraft*, *AircraftComponent* etc, become Java Classes, which can then have class instance properties themselves, again represented by attributes. In this way, a recursion occurs: an element becomes a new class, and each property of it is examined. If the property is an attribute, a simple Java primitive member variable is created for the object; if the property is element, a new data object type is created, added as a member variable, and the process begins again on the new object type, until all classes are created. All other aircraft components and disciplinary data can be similarly created. A Unified Modeling Language (UML) diagram for generated Java class (only wing component is shown) is illustrated in Figure 6. The generated classes also ensure that all the hierarchical data object structure and their internal relationships are properly maintained. For example, the figure shows that Wing is a *subclass* that extends *AircraftComponent*, therefore, it inherits all states and behaviors from its ancestor.

In addition, the generated classes provide methods

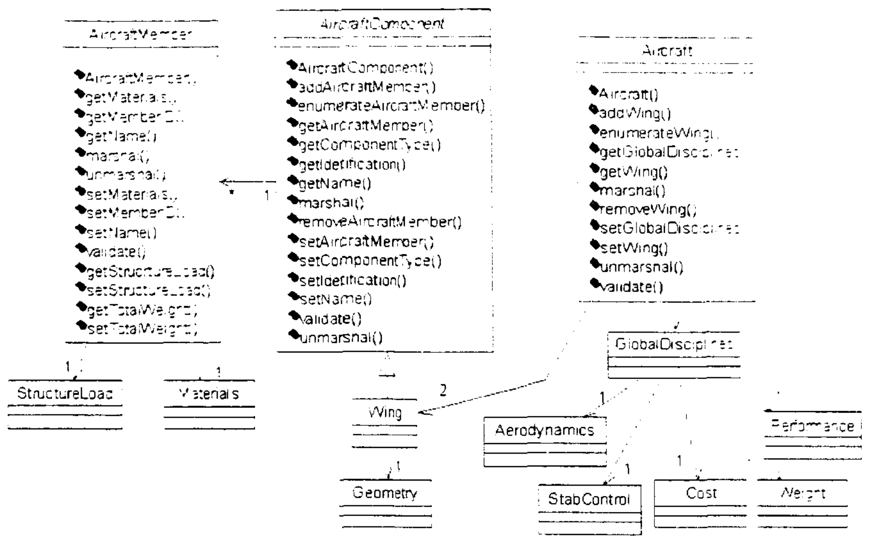


Figure 6. UML for Data class structure generated by aircraft databinding

to access and modify the properties defined in the aircraft Schema. These methods closely follow the JavaBean Design Pattern [21]. The main guideline for the design pattern is that all publicly accessible fields have proper getter (accessor) and setter (mutator) methods. For a given field, a getter method is quite simply a method that returns the value of that field, while a setter method is one that allows us to set the value of the field. Each method signature specifies the name of the operation, which is sufficient for design tools to obtain information about the fields of data classes by examining the method signatures of a given class. This examination process is called *Introspection*.

For each aircraft data class that is automatically generated (e.g. *AircraftComponent*), there is also included a set of *marshal*, *unmarshal* and *validate* methods, with their method signatures like:

```
public boolean validate()
public void marshal(Writer out)
public AircraftComponent unmarshal(Reader reader)
```

The `validate` method is used to check whether the aircraft data contained in XML file is valid, i.e. conform to its corresponding data schema; `marshal` and `unmarshal` methods can be used to map directly to the data of elements and attributes within the XML document and also affect the underlying aircraft data. This is achieved through underlying Marshalling Framework design.

Marshalling Framework

The marshalling framework supports the transportation (unmarshal) of aircraft data in XML files into graphs of interrelated instances of aircraft objects that are generated during schema complier and also converts (marshal) such graphs back into XML file. For example, when XML-based wing data is correctly unmarshaled into aircraft Java codes, the Wing node in the XML file becomes an instance of the Wing class that was generated by aircraft Schema Compiler, i.e. Wing Data Object. The aircraft design system can then interfaces those objects, and all interactions and manipulations of aircraft disciplinary data in a design system can be described as invocations of operations on those objects. In particular, the aircraft design application can use the corresponding methods devised with a set of mutator and accesor methods to work with the aircraft data in the underlying design data file. Therefore, it provides a convenient way to access and modify the aircraft data where all underlying files are transparent to the user. The end result is aircraft data binding.

Distributed Access

As the argument in `marshal` is a general "writer" object, it can be piped to or wrapped into many other different writers or streams, such as a network connection, or another program. This means marshaling can be done remotely from aircraft disciplinary design team servers (Figure 7). The same applies to unmarshaling process where a general "Reader" is used. A set of sample disciplinary drivers have been written that use HTTP socket connection, Java Servlet, CORBA, RMI technology to allow the databinding to be called from different client working environments. These discipline drivers can serve as a 'plug-in' for aircraft disciplinary simulation codes and enables them to use XML-based aircraft data easily and remotely.

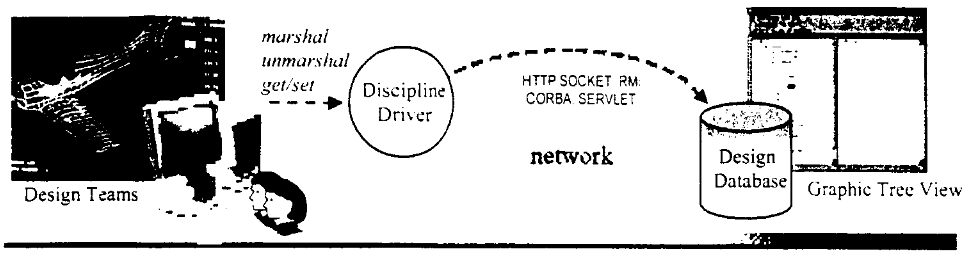


Figure 7. Design teams use Marshal Framework to access aircraft data remotely

According to the design requirements, more than one discipline data may need to be called by a driver. The interfaces between the discipline codes and their drivers must be accurately specified in order to provide proper communications. The disciplinary drivers can also serve as templates or examples for more complex problems.

Dynamically Schema Add-in

With advances in aircraft design process, there has been an increased realization that new disciplines, such as maintainability, productivity, etc., should be addressed in order to optimize the aircraft design process. Aircraft databinding also provides a service that can dynamically add-in new aircraft disciplinary schemas. These schemas can be either in XML-schema format or in DTD format, but they must conform to a set of newly designed disciplinary data object models. *STEPConverter* is an example of this service that provides a set of tools and libraries to read and write STEP Part28 compatible DTD file and to be used for aircraft geometry modeling (Figure 5). By using add-in support to aircraft disciplinary schema, the databinding code itself is kept generic and does not need any special coding for a new problem.

Performance

Since XML description of aircraft data are by their nature potentially large in size, in order to improve aircraft database performance, the databinding internally integrates another service, through XInclude [12] and XLink [13], that further allows users to split an arbitrary large aircraft data file into a sequence of sufficiently small subfiles during the marshalling process, and resemble all these pieces together when unmarshaling XML-based aircraft data to their data objects. This kind of flexibility allows an aircraft data file to span multiple physical files reside in different computers by referencing as URI, and also make possible a portion of one aircraft data file to be referenced by several other aircraft files. The individual files are more portable due to their reduced size, and make use of less memory to represent the whole necessary layered tree of the aircraft data nodes. In addition, a *ZipArchiver* is included in the aircraft databinding, which will compress the aircraft data in XML subfiles into different Zip entities in an aircraft archive when transferring aircraft data objects to data files. By using text compression algorithms, the XML data file size can be much smaller than the original size and even smaller in size than binary representation of the same data. This reduces file I/O access times and improves performance required for large aircraft dataset.

CONCLUSION

In this work, a XML-based database model for use in multidisciplinary aircraft design has been designed, which meets design requirements of diverse disciplines. The database consists of data object models, database schemas, and data binding. Aircraft Data Object (ADO) model encompasses most of common components involved in multidisciplinary aircraft design, as well as various pertinent disciplines, such as aerodynamics, structures, cost, materials, performance, stability and control and weights. STEP AP203 standard is used to describe each component's geometry data. The ADO model precisely defines the organizational structure supporting aircraft design data and the conventions adopted to standardize the data exchange. This is particularly important when trying to transfer data between different disciplines and different storage models, as there must be agreed-upon data structure and syntax for different systems to understand each other.

In order to store and validate XML-based aircraft data, a set of database schemas was designed based on ADO model. By using XML Schema to represent aircraft Schema, a set of constraints establishes how domain-specific data should be constructed, which can then be used to further schema-validate the aircraft data, ensuring that the contained data are valid. The database schema follows a modular design pattern such that it is extensible for future addition and/or modification. By using and developing focused aircraft disciplinary schema for specific aircraft component object types, users can benefit by an increase in application reusability.

The aircraft databinding provides an object interface to various aircraft disciplines, allowing automated storage and retrieval of XML-based aircraft design results within and across disciplines. Most of the data manipulation services are transparent to the aircraft designer and simulation codes. This higher level database development with automation support provides a common working environment, which would enhance the productivity of multidisciplinary projects.

Since all disciplinary data in the binding process are stored in XML documents, they bypass the requirement to have a standard binary encoding or storage format. Additionally, the language independent representation of various aircraft component and disciplinary data can foster interoperability amongst heterogeneous systems, and thereby greatly facilitates the multidisciplinary aircraft design.

ACKNOWLEDGMENTS

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AIAA 2002- 4058

Interactive, Secure Web-enabled Aircraft Engine Simulation Using XML Databinding Integration

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INTERACTIVE, SECURE WEB-ENABLED AIRCRAFT ENGINE SIMULATION USING XML DATABINDING INTEGRATION

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ABSTRACT

This paper discusses the detailed design of an XML databinding framework for aircraft engine simulation. The framework provides an object interface to access and use engine data, while at the same time preserving the meaning of the original data. The Language independent representation of engine component data enables users to move around XML data using HTTP through disparate networks. The application of this framework is demonstrated via a web-based turbofan propulsion system simulation using the World Wide Web (WWW). A Java Servlet based web component architecture is used for rendering XML engine data into HTML format and dealing with input events from the user, which allows users to interact with simulation data from a web browser. The simulation data can also be saved to a local disk for archiving or to restart the simulation at a later time.

INTRODUCTION

Computer programs capable of simulating the operation of aircraft engines are useful tools that can help reduce the time, cost and risk of product design and development and facilitate learning about the complex interactions between jet engine components. However, the strongly-coupled nature of the components' flow physics and the large number of operating and design parameters needed for simulation of the aircraft engine system present a challenge to developers who aim at designing an easy-to-use and effective engine simulation program for users. Most of the aircraft engine simulation software currently available have limitations primarily in the presentation of the simulation input and output data, due to the use of text-based interfaces, and the lack of data validation methods. As a result, engine simulation results could be overwhelming and difficult to interpret without a significant effort. Moreover, traditional simulation data are, in general, stored in proprietary data formats and constrained by hardware and operating system platform differences. Thus, developers are hindered in their efforts to synthesize simulation data in their design unless a clearly defined and interoperable data interface exists. The bottlenecks caused by data handling, heterogeneous computing environments and geographically separated design teams, continue to restrict the use of these tools [1].

Web-based simulation, due to its accessibility, convenience and emphasis on collaborative composition of simulation models, distributed heterogeneous execution, and dynamic multimedia documentation, has the potential to fundamentally alter the practice of simulation [2]. Presently, the majority of work in web-based simulation has centered on re-implementation of existing distributed and standalone simulation logics *within* Java Applets [3,4]. Applets are quite popular because they are supported by common browsers and are safe to execute on client computers. However, with the whole simulation code *tightly-bound* to an Applet, it may take a long time for the rich engine simulation code to load within a client's browser. In addition, it is often not efficient to execute complicated simulation logic at the client side, where a high performance computer is generally not available. Applets' security model, arguably one of its strengths, also creates obstacles for post-processing of simulation data beyond what applets provide since it inhibits creation of data files on the host machine.

This paper describes a web-based aircraft engine simulation system, called *X-Jgts*, through dynamic XML databinding framework which permits data communication with ease. XML [5], due to its structured, platform and language independent, highly extensible and web-enabled nature, has rapidly become an emerging standard to represent data between diverse applications. XML can represent both structured and unstructured data, along with its rich descriptive delimiters. By using XML to represent engine data in high performance propulsion system simulation, it is possible to faithfully model the structural elements of a chosen component in an interoperable fashion that is natural in their simulation context. Since HTTP (Hyper Text Transfer Protocol) already supports transmission

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of plain text, XML data can be moved around readily using the HTTP through firewalls and disparate networks. Engine databinding through XML also provides simulation designers with a higher and more user-friendly API to work with underlying engine components repository and thus enables the components to communicate with each other effectively.

ENGINE MODELS

This section provides an overview of engine analysis model that is used in our web-based simulation. Also presented is the designed engine data object model that will be used in engine databinding framework.

Analysis Model

The mathematical model used to describe the operation of the gas turbine system in the current work is patterned after that presented in [6]. Here, the gas turbine system is decomposed into its individual basic components: inlet, compressor, combustor, turbine, nozzle, bleed duct connecting duct, and connecting shaft. Intercomponent mixing volumes are used to connect two successive components as well as define temperature and pressure at component boundaries. Operation of each of the components is described by the equations of aero-thermodynamics which are space-averaged to provide a lumped parameter model for each component. For dynamic (transient) gas turbine operation, the model includes the unsteady equations for fluid momentum in connecting ducts, inertia in rotating shafts, and mass and energy storage in intercomponent mixing volumes. A complete description of the model can be found in [7].

Data Object Model

Based on the above engine analysis model, an "Engine Data Object" (EDO) model was designed to precisely define the intellectual content of engine component data, including a complete definition of engine data entities, attributes, relationships, and specification of local and global constraints on these entities.

In order to effectively represent simulation data using XML, the engine system, shown in Figure 1(a), was first decomposed into individual basic components in a strict hierarchical manner in accordance with the XML topology. A set of data structures is then built in parallel with each engine component. An overall layout of a simplified data model is summarized in Figure 1(b). Each node in the model shown here is represented as an engine data object. The figure also indicates (informally) what data, if any, are encapsulated within each node object. For example, the *Nozzle* data object shown in Figure 1(c) gives information about a particular converging-diverging or converging-only nozzle in an engine simulation. The user-defined parameters of a nozzle include a set of nozzle design point data and nozzle initial operating data, such as mass flow rate, throat area, exit area, gross thrust, etc. Consequently, these data are designed as subchildren data objects in *Nozzle*. In addition, the nozzle throat and exit areas may be adjusted during the transient by a user-defined schedule; *ThroatAreaTransientControllers* and *ExitAreaTransientControllers* are designed for this

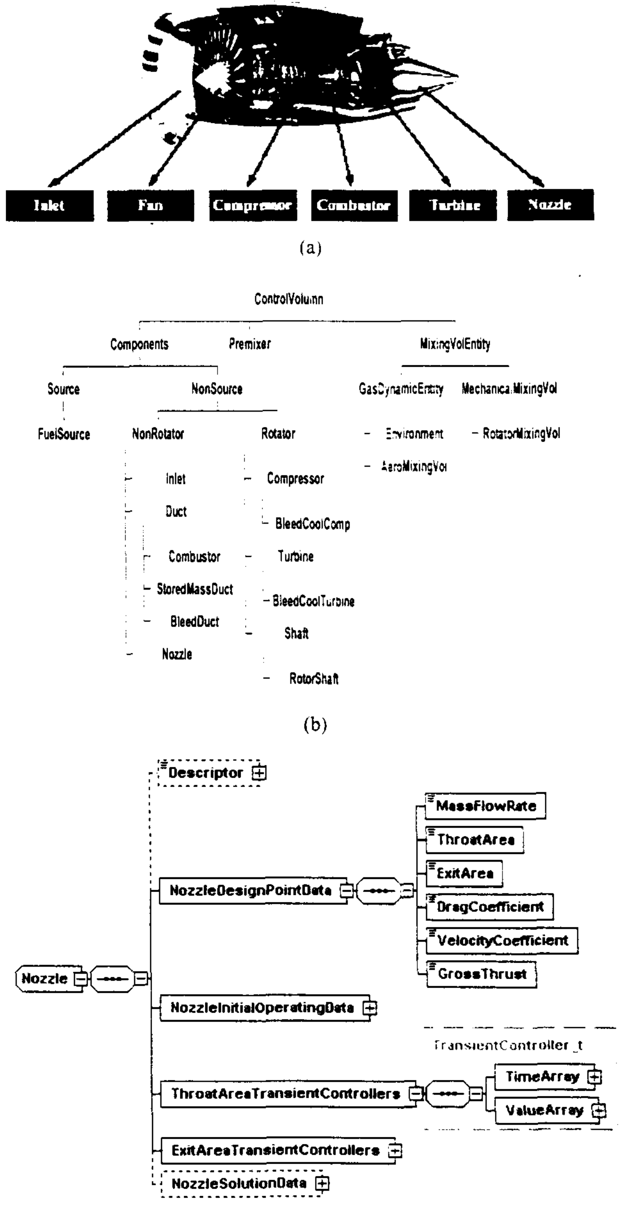


Figure 1 (a) decomposition of engine component; (b) hierarchical engine data object model; (c) subchildren objects inside nozzle data object

purpose. *NozzleSolution* object is used to store the solution datasets after a simulation, which itself contains other children data objects that are not shown here. An optional *Descriptor* object can also be included to describe nozzle operating status.

ENGINE DATABINDING FRAMEWORK

Based on our data object model design, an Engine Data Binding (EDB) Framework has been implemented in Java to facilitate binding an engine data object into a data entity in XML-based engine data file. The framework makes it easy to convert between the engine data stored in XML file and their object representations, and facilitates the applications to access, modify and store any engine component data object. Figure 2 gives a schematic representation of all components in engine databinding framework. Engine databinding framework can also be run as a standalone application [8].

Engine Schema

Engine schema establishes a bridge between XML-based engine data and its data object model. It associates each piece of the information defined in the data object model to a precise location in the XML structure. A set of engine schemas have been designed using XML Schema language [9] that specifies how the constituents of the engine data objects are mapped to an underlying XML-based engine data structure. The rules in the data model will guarantee that the schema description of engine data is syntactically correct and also follows the grammar defined within it.

Figure 3 shows a sample schema representation for the *Nozzle* and one of its children, *TransientController*, which is used to supply transient control parameters for throat and exit areas. Based on the Nozzle data model shown in Figure 1(c), the "Nozzle" schema defines all the data elements that are contained in a single nozzle data object. These elements are constrained by their corresponding complexTypes and simpleTypes and encapsulated in the *Nozzle* object. For example, *NozzleDesignPointData* defines all its permitted data variables, such as *MassFlowRate*, *ThroatArea* etc, and their corresponding data types, which are built-in double type. Also note that in the above Nozzle schema only *NozzleDesignPointData* element is explicitly defined, the rest of its element definitions use the "ref" attribute to tell the data parser in the engine simulation that the definition for these elements are defined in other schema files with the same target namespace (i.e, the default "engine" namespace in Fig.3) as nozzle. These 'ref'ed schema will be automatically included by schema parser during the run time. This kind of flexible design will guarantee that all the basic schema types can be reused. Moreover, it will allow for modular development and easy modification of engine schema as engine data object model evolves in the future.

Schema Compiler

The engine schema compiler is designed to map an instance of an engine schema into the appropriate engine data object model. It *automatically* translates an engine-specific schema into a set of derived engine data object models (set of classes and types which represent the data) with appropriate access and mutation (i.e., get and set) methods that can be used to affect the underlying engine data files. Figure 4 shows an example of how a generated class should correspond to the nozzle schema defined in the previous section. With the "Nozzle" schema defined, attributes are *"compiled"* into simple Java types, usually primitives; element (along with its type information which specifies the content model) becomes engine data class, with

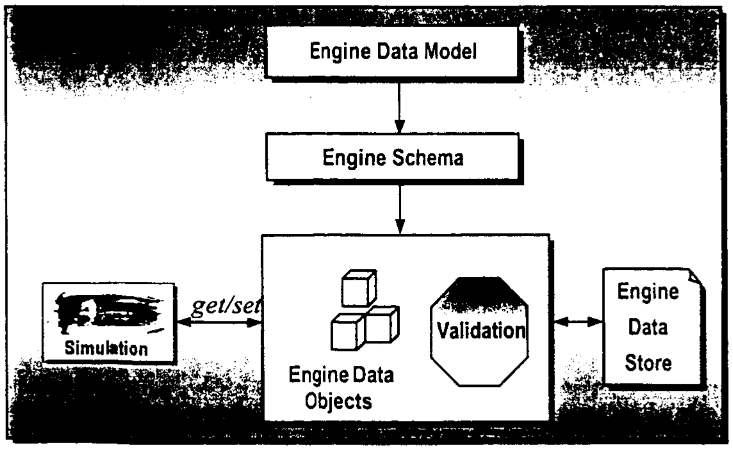


Figure 2. Engine databinding framework

```
<?xml version="1.0"?>
<xsd:schema targetNamespace="http://mems1.nl.utoleco.edu/engine"
    xmlns.xsd="http://www.w3.org/2001/XMLSchema"
    xmlns="http://mems1.nl.utoleco.edu/engine" elementFormDefault="qualified" version="1.0">
   <xsd:include schemaLocation="TransientController.xsd"/>
   <xsd:include schemaLocation="Descriptor.xsd"/>

   <!-- ComplexType Nozzle_t is designed to constraint Nozzle -->
   <xsd:complexType name="Nozzle_t">
        <xsd:sequence>
            <xsd:element name="Descriptor" type="Descriptor_t" minOccurs="0"/>
            <xsd:element name="NozzleDesignPointData">
                <xsd:complexType>
                    <xsd:attribute name="MassFlowRate" type="xsd:double"/>
                    <xsd:attribute name="ThroatArea" type="xsd:double"/>
                    <xsd:attribute name="ExitArea" type="xsd:double"/>
                    <xsd:attribute name="DragCoefficient" type="xsd:double"/>
                    <xsd:attribute name="VelocityCoefficient" type="xsd:double"/>
                    <xsd:attribute name="GrossThrust" type="xsd:double"/>
                </xsd:complexType>
            </xsd:element>
            <!-- NozzleInitialOperatingData element is similarily designed
                and ommitted here for simplicity-->
            <xsd:element name="ThroatAreaTransCntl"
                        type="TransientCntl_t"/>
            <xsd:element name="ExitAreaTransCntl"
                        type="TransientCntl_t"/>
            <!—All NozzleSolutionData elements and ommitted for simplicity-->
        </xsd:sequence>
        <xsd:attribute name="Name" type="xsd:string" use="required"/>
   </xsd:complexType>
</xsd:schema>
```

```
<?xml version="1.0"?>
<xsd:schema xmlns xsd="http://www.w3.org/2001/XMLSchema"
      elementFormDefault="qualified" version="1.0">

     <!-- TransientController complexType -->
     <xsd:complexType name="TransientCntl_t">
          <xsd:sequence>
               <xsd:element name="TimeArray" type="doubleDatalist"/>
               <xsd:element name="ValueArray" type="doubleDatalist"/>
          </xsd:sequence>
          <xsd:attribute name="name" type="xsd:string" use="optional"/>
     </xsd:complexType>

     <xsd:simpleType name="doubleDatalist">
          <xsd:list itemType="xsd:double"/>
     </xsd:simpleType>
</xsd:schema>
```

Figure 3. Engine schema representation of *Nozzle* and *TransientControl* data object model

```
//– all the Java import statements here

public class Nozzle implements java.io.Serializable {
   private String _name;
   private Descriptor descriptor;
   private DesignPointData _nozzleDesignPointData;
   private InitOperatingData _nozzleInitOperatingData;
   private ThroatAreaTransCntl _throatAreaTransCntl;
   private ExitAreaTransCntl _exitAreaTransCntl;
   private NozzleSolutionData _nozzleSolutionData;

   public Nozzle() {
      super();
   }
   public String getName() {
      return this._name;
   }
   public void setName(String name) {
      this._name = name;
   }
   public ExitAreaTransCntl getExitAreaTransCntl() {
      return this._exitAreaTransCntl;
   }
   public void setExitAreaTransCntl(ExitAreaTransCntl  exitAreaTransCntl) {
      this._exitAreaTransCntl = exitAreaTransCntl;
   }

   //– the same with all other types and are omitted here

   public boolean validate()
          throws EngineValidationException  {
       try {
              Validator validator = new Validator();
              validator.validate(this); }
       catch (EngineValidationException vex) {
              return false;
       }
       return true;
   }
   public void marshal(java.io.Writer out)
          throws MarshalException, EngineValidationException {
     Marshaller.marshal(this, out);
   }
   public static Nozzle unmarshal(java.io.Reader reader)
          throws MarshalException, EngineValidationException {
     return (Nozzle)Unmarshaller.unmarshal(Nozzle.class, reader);
   }
}
```

Figure 4. *Nozzle* data class generated by schema compiler process

generated data types and properties encapsulated in it. The generated class provides pairs of accessor (*get*) and mutator (*set*) methods for all the properties defined in engine schema, which closely follows the JavaBean Design Pattern [10].

In addition, the engine schema compiler can generate the data 'validation' class code so as to enforce the constraints expressed in the schema. The code generated by the valid schema translation will check that incoming engine data files are 'legal' with respect to the constraints defined in schema, thereby ensuring that only valid XML-based engine data files are produced by the marshalling process.

The generated Java classes also include a set of *marshal*, and *unmarshal* methods that can be used to "translate" engine application data from/to engine data objects automatically. These are achieved through an underlying Marshalling Framework design.

Marshalling Framework

The marshalling framework supports the transportation (*unmarshal*) of XML-based engine data into "graphs" of interrelated instances of objects that are generated by engine schema complier and, in addition, converting (*marshal*) such graphs back into engine data stored in XML documents. The marshal method works by taking a desired *Writer* object as argument and then returning an XML element representation of that object. If the object contains references to other engine data objects, then recursion can be used, using the same method. The same applies to unmarshaling process where a general *Reader* is used. When the engine data are correctly unmarshaled, each element node in the XML file becomes an instance of the data class that was generated by engine schema compiler, i.e. engine data object. Then, the engine simulation components can use the corresponding methods, along with a set of *mutator* and *accesor* methods, to work with the engine data in the underlying data file. The end result is engine data binding.

SIMULATION ARCHITECTURE

X-Jgts is a web-based, interactive, graphical, numerical gas turbine simulator which can be used for the quick, efficient construction and analysis of arbitrary gas turbine systems. It also provides a systematic, meaningful data presentation and secured data operation scheme with the support of a built-in data binding framework. Figure 5 illustrates the overall simulation architecture described in this paper, as well as its major components and the interactions between web client and simulation server.

Web Client

In *X-Jgts* system, the client user interface is delivered through a web browser. The web browser is a universal user interface that is responsible for presenting engine simulation data, issuing requests to the simulation web server, and handling any results generated at the request of the user. *X-Jgts* uses both dynamically generated HTML and Swing-based Java Applet to properly present user-friendly data; in particular, HTML is used to display simulation results, while Swing-based Applet is used for graphic data display. The platform-independent nature of HTML and Java Applet enables the engine simulation to be widely conducted from heterogeneous, networked computers.

As a general rule for web-based simulation, application logic should not be implemented on the browser. Complex simulation logics that are tightly built into Applets are normally inefficient to execute due to the fact that client side users generally lack powerful computing resource. In addition, it may take quite a long time for a client's browser to load. Therefore, the browser, HTML, and Swing Applets designed in *X-Jgts* are used strictly for delivering the user interface and view into the engine simulation. The user requests are made either from the front-end Applet or HTML code to perform designate tasks remotely in the simulation web server.

Simulation Server

Engine simulation server is a dynamic extension of a Web server and the heart of any web interactions. It uses HTTP as protocol for communication and consists of static resources, such as the front end simulation Applet, as well as dynamic web pages (HTML) that are generated by different engine web components hosted in the server. The web server listens for incoming requests and then services the requests as they come in. Once the server receives a simulation request, it then springs into action. Depending on the type of request, the web server might look for a web page, or execute a web component on the server. Either way, it will return some kind of results to the web client.

In *X-Jgts*, engine web components are sets of

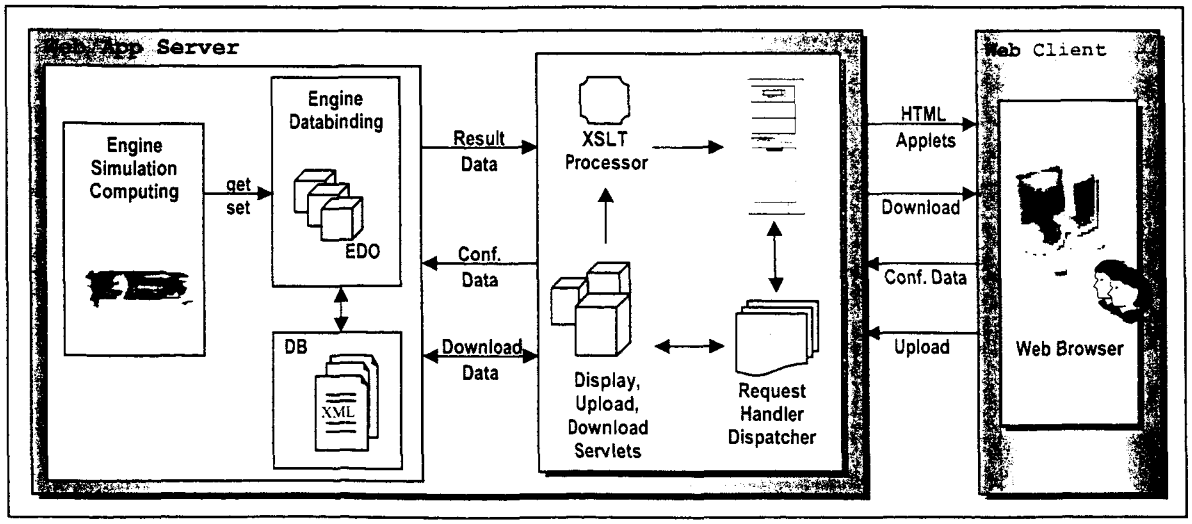


Figure 5. Web-based simulation architecture in *X-Jgts*

simulation task-related Servlets [11] or JavaSever Pages [12]. Servlet/JSP provides a platform-independent means of extending a web server's capabilities. When a user issues a request for a specific Servlet, the server will simply use a separate thread and then process the individual request. This has a positive impact on performance.

Engine web components are running in the Tomcat [13] Web container to dynamically process various simulation requests and construct responses. The web container provides services such as request dispatching, security, concurrency, and life-cycle management. Based on different task-related services, engine web components may invoke other web resources directly through embedded URLs that point to other web components while it is executing, or indirectly by forwarding a request to another resource using *RequestDispatcher*. There are four main services currently available in the engine simulation server.

Simulation Web Component

Engine simulation service is a core web component that provides a transient, space-averaged, aero- and thermo-dynamic gas turbine analysis for a web client based on the engine analysis model. Besides that, the simulation web component includes the built-in engine databinding support and an underlying XML-based engine database repository to store simulation data (Figure 5). During the engine simulation, the verification logics that are automatically generated by engine schema compiler can be applied inside the simulation so that the users' inputs and simulation outputs could be checked. Engine components can also conveniently manipulate the engine data with a set of *accessor* and *mutator* methods devised from databinding framework. When a simulation completes, engine components can readily *marshal* sets of engine object data into the underlying data repository for storage and *unmarshal* them back to engine data objects later when data manipulation is necessary. This feature gives a very useful and natural way for the storage of any engine data object and provides the engine simulation with unambiguous, meaningful and interpretable representation of engine data sets. The engine simulation service can also generate simulation graphs and transcript data dynamically and send them to the front-end Applet for display.

File Download Web Component

X-Jgts allows users to save their simulation results to the local file system so that users can redisplay their simulation result or restart simulation at a later time. This is achieved internally by the file-download service. Due to security reasons, current web browsers prohibit the front-end simulation Applet from directly writing data files on the host that is executing it. Nevertheless, Applets can usually make network connections to the host they came from. In *X-Jgts*, whenever a user wants to download a complete simulation result or engine configuration file, the front-end Applet will make a request to file-download service resided on the simulation web server, locate the corresponding case file from database repository and then generate a download response to the user. By setting the HTTP `Content-Disposition` response header as *attachment*, Web browser at client side will pop up a "save as" box to let user save simulation result.

File Upload Web Component

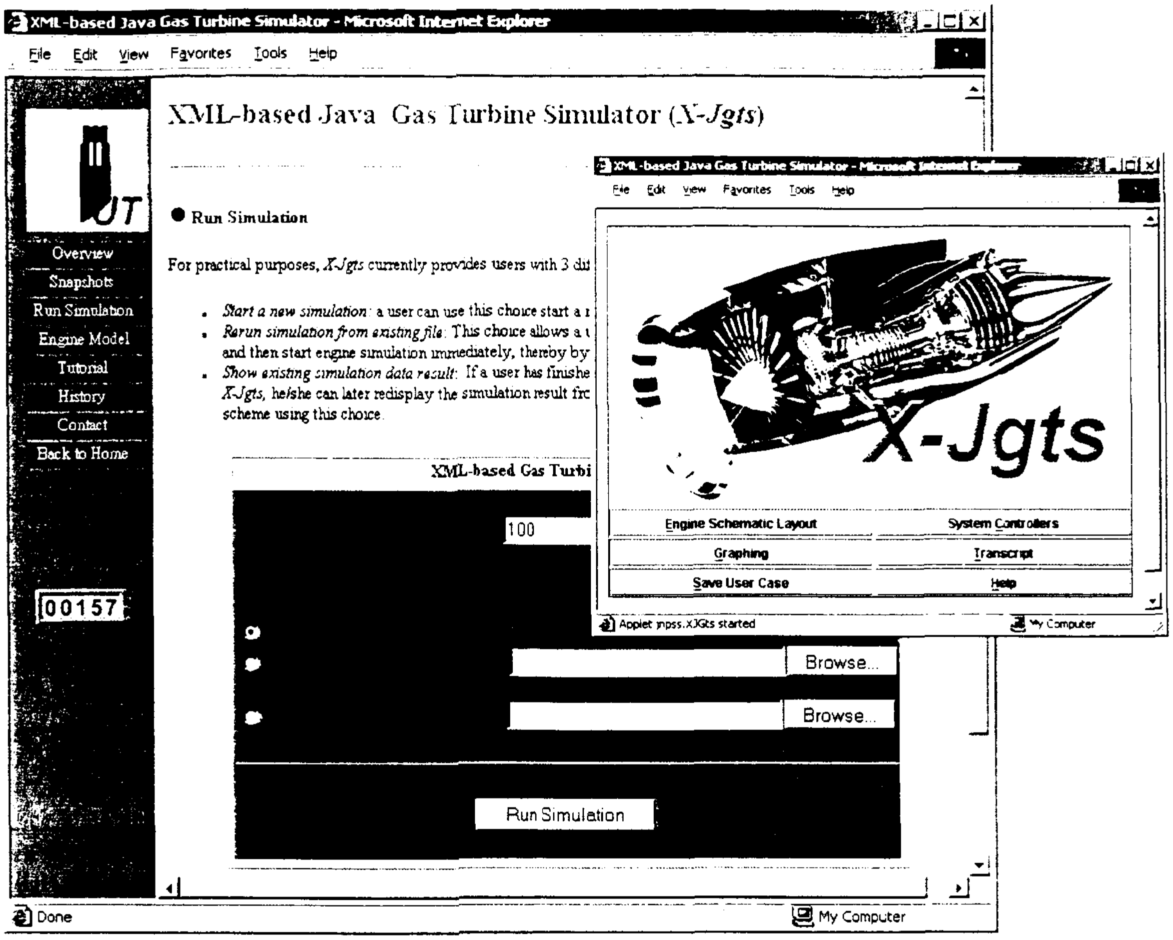
At times users have a requirement to upload a file from their local file system to the web server for display of engine simulation result in a more meaningful way. *X-Jgts* web components include a Servlet that can receive a file upload using its input stream. When a file is sent via a browser, it is embedded in a single POST request with *multipart/form-data* [14] encoding type. The file upload Servlet will take in the part of this multipart data stream, reassembled and encoded on the server, and then dispatch the processing results to display service, where dynamically generated engine data file in HTML format are sent to client's browser for display.

Display Web Component

Since engine data are stored in XML file format, it is easier to apply certain transformation logic such that simulation results can be displayed in a more friendly way within the user's browser. XSLT [15] provides a way to transform the engine data without cluttering up the web components code with HTML. When the simulation server receives a display request, the build-in XSLT processor knows how to parse engine component-specific XSLT style sheets and apply transformations. Best of all, a clean separation between engine data, presentation, and simulation logic allows changes to be made to the look and feel of a web site without altering the simulation code. Because XML-based engine data can be transformed into many different formats, it can also achieve portability across a variety of browsers and other devices.

DEMONSTRATION

Based on the designed data object model, databinding architecture, and simulation architecture, a web-based engine simulation has been implemented that internally uses *Onyx* [16] as the engine simulation logic. Onyx is an object-oriented framework for propulsion system simulation. Figure 6 shows the XML-based Java Gas Turbine Simulator, *X-Jgts*, being accessed from an Internet Explorer browser.


XML-based Java Gas Turbine Simulator (*X-Jgts*)

● Run Simulation

For practical purposes, *X-Jgts* currently provides users with 3 di

- *Start a new simulation*: a user can use this choice start a
- *Rerun simulation from existing file*: This choice allows a
  and then start engine simulation immediately, thereby by
- *Show existing simulation data result*: If a user has finishe
  X-Jgts, he/she can later redisplay the simulation result fr
  scheme using this choice.

Figure 6. XML-based Java Gas Turbine Simulator accessed from a Web browser

For practical purposes, *X-Jgts* currently provides users with 3 different kinds of simulation services. A simulation identifier (ID) is required to perform each service.

<u>Start a new simulation</u>

A user can use this choice to start a new engine simulation in interactive construction mode. After the user enters a simulation ID, and starts to perform the simulation, the Swing-based Applet interface (Figure 6) will appear. From there the user can access the various main windows of the simulation system: *Engine Schematic Layout*, *System Control Dialog*, *Graphing*, *Transcript*, or *Save User Case*.

Before each simulation is run, the user must provide each individual engine component with initial simulation configuration data from the designed *Engine Schematic Layout Dialog* (see Figure 7). An engine model is developed by building an engine component schematic graphically as *Icons* (e.g., BleedDuct, Nozzle, VariableCompressor, etc.) and connecting them together. In the diagram, the arrowheaded connecting lines represent both the directional flow path for fluid through the engine, and the structural connections along which mechanical energy is transmitted. The user can define the operational characteristics for the component (i.e., the component name, design- and initial-operating point data, etc.) in the engine component's dialog window (Figure 8). The *System Control Dialog* (Figure 9) provides controls for the overall operation of the simulation. The steady-state numerical solver is used to balance the gas turbine equations at the initial operating point as was defined by the user; while transient solvers are used for dynamic engine performance analysis. When the necessary data input for simulation configuration is finished, the simulation can have the option to start simulation immediately or download the configuration file and run it later.

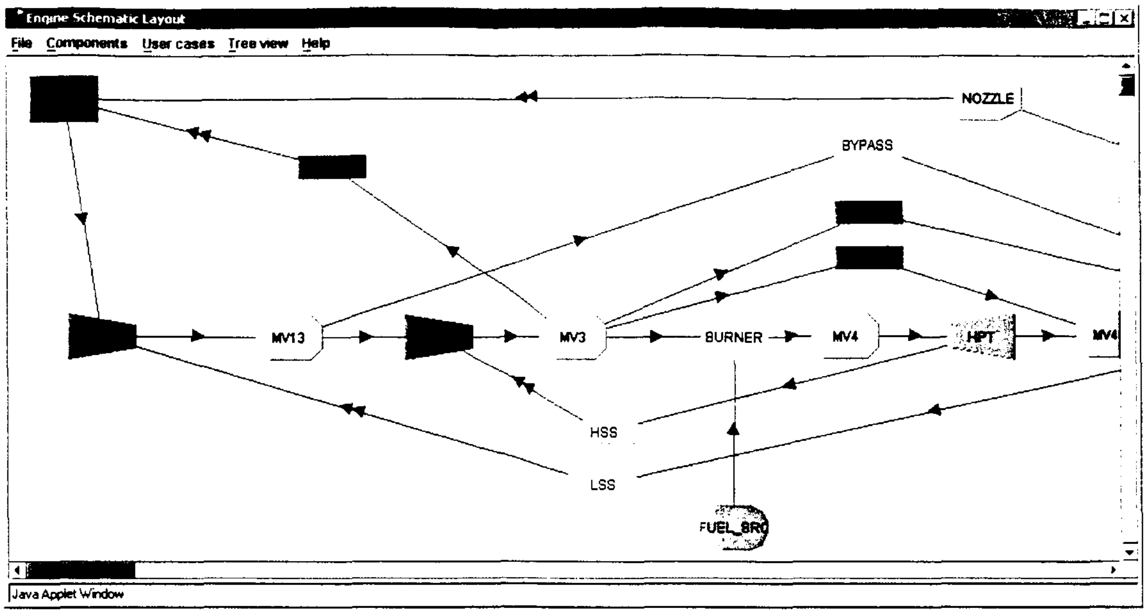
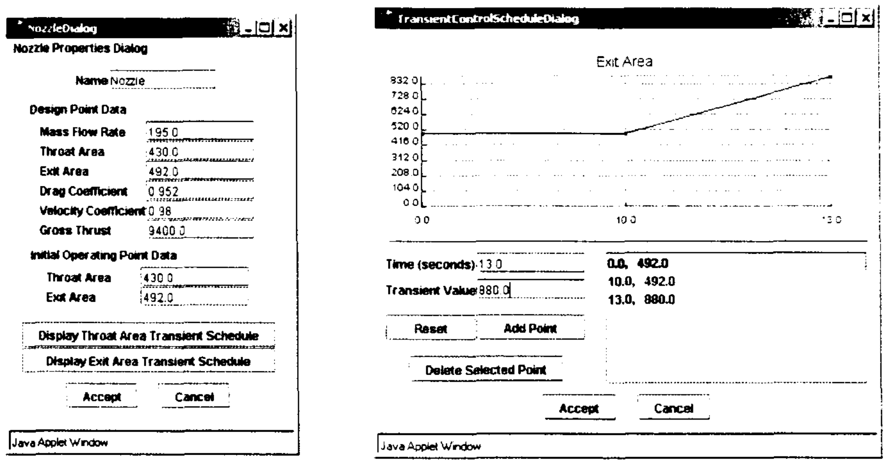


Figure 7. Engine schematic layout dialog



Nozzle Properties Dialog

Name	Nozzle
Design Point Data	
Mass Flow Rate	195.0
Throat Area	430.0
Exit Area	492.0
Drag Coefficient	0.952
Velocity Coefficient	0.98
Gross Thrust	9400.0
Initial Operating Point Data	
Throat Area	430.0
Exit Area	492.0

Display Throat Area Transient Schedule

Display Exit Area Transient Schedule

Accept Cancel

Time (seconds)	13.0
Transient Value	880.0

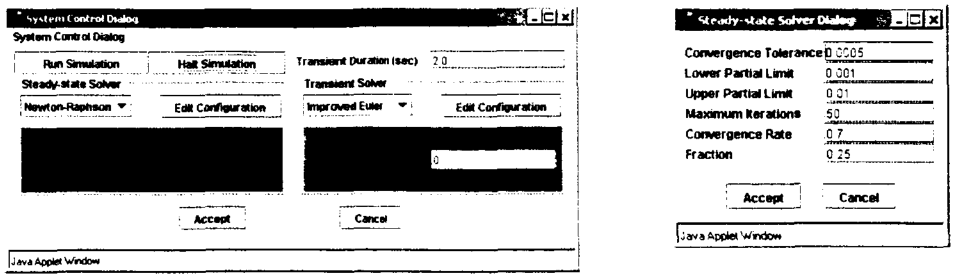
0.0, 492.0
10.0, 492.0
13.0, 880.0

Reset Add Point

Delete Selected Point

Accept Cancel

Figure 8. Dialogs used to set engine component (Nozzle) operational characteristics



System Control Dialog

Run Simulation Halt Simulation

Transient Duration (sec)	2.0
Steady-state Solver	Newton-Raphson
Transient Solver	Improved Euler

Edit Configuration Edit Configuration

0

Accept Cancel

Convergence Tolerance	0.0005
Lower Partial Limit	0.001
Upper Partial Limit	0.01
Maximum Iterations	50
Convergence Rate	0.7
Fraction	0.25

Accept Cancel

Figure 9. Engine simulation system control dialog

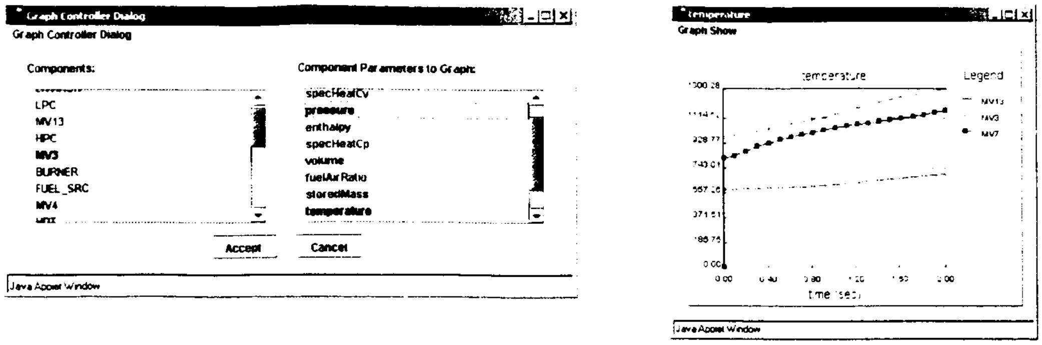


Figure 10. Graphically display engine component parameters

Once a simulation begins, the engine configuration data will be encoded in XML format and sent over the Internet to the web simulation server. When the server receives the engine configuration file, it then automatically dispatches the file to the simulation web component, where engine databinding and simulation logic are performed. At the same time, the user can select from *Graph Control Dialog* (Figure 10) to plot a number of specified parameters for any of the components currently displayed in the *Engine Schematic Layout* window. The user may also view simulation status reports, using the *Transcript* button shown in Figure 6, that are sent from simulation web server during the simulation. Once the simulation is completed, the simulation web component will marshal all engine data objects into an engine data file designated by its simulation ID, and store it into the database repository. Finally, the user can use *Save User Case* button to download the complete solution of the simulation case for later use.

Rerun simulation from an existing file

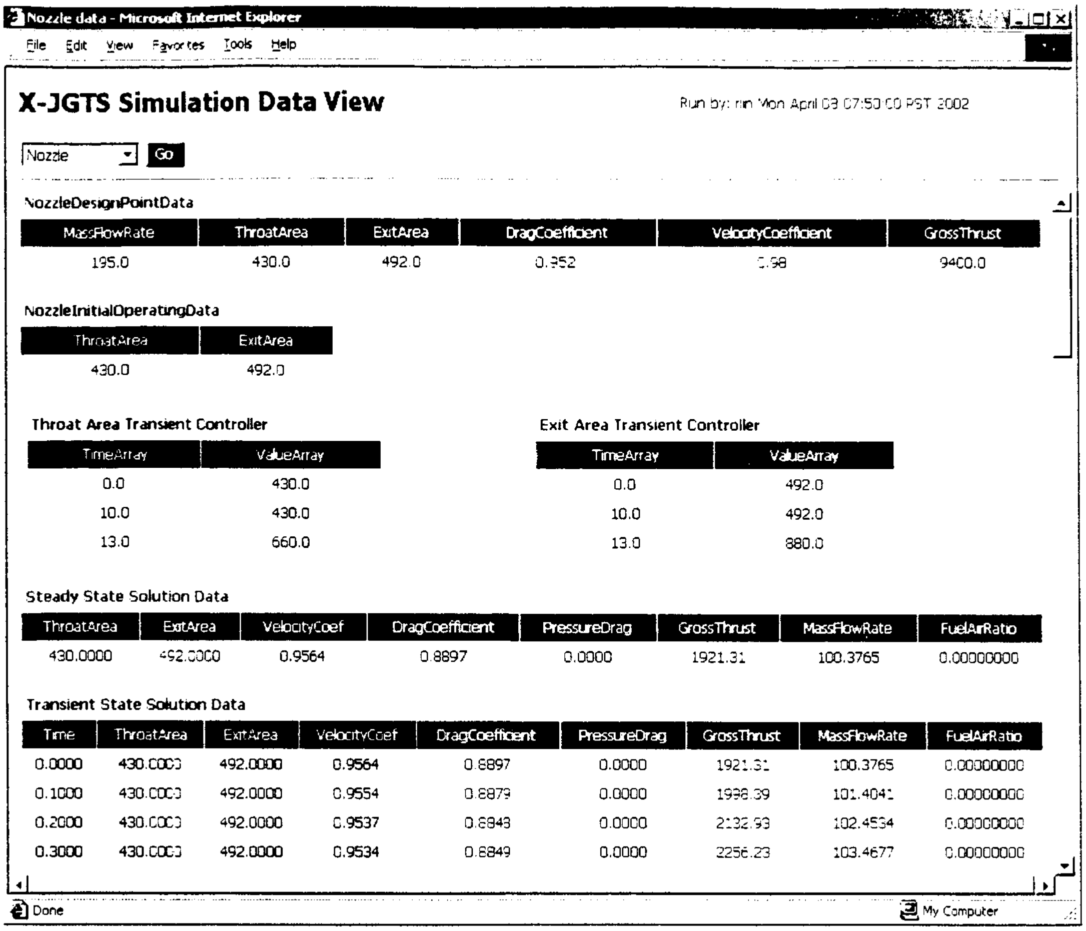
X-Jgts also provides a service for users to directly input engine simulation configurations from a file, which allows bypassing the engine construction procedures. Part of a sample configuration file is shown in Figure 11. When a user uploads the configuration file from a web browser (Figure 6), all the defined simulation parameters will be immediately available from *Engine Schematic Layout Dialog* and *System Control Dialog*. Users can then use *User cases* menu in *Engine Schematic Layout* to verify these configurations. Users can also edit these data using the above two dialogs. In this case, the updated configuration file will be sent to the server to run the simulation.

Show existing simulation data results

If a user has finished an engine simulation case and saved the simulation data using *X-Jgts*, he/she can later redisplay the simulation results in a web browser with a more meaningful data presentation scheme using this service. In this case, when the web simulation server receives an engine simulation case file uploaded from the user's web browser (Figure 6), it will internally use *Display Web Component* (combined with sets of pre-designed XSLT style sheets) to dynamically generate HTML code for display within the user's browser. Figure 12 shows the nozzle data file from an example simulation case. The user can choose different engine components to display from the drop-down list at the top of the web page.

```
<?xml version="1.0"?>
<EngineRoot xmlns="http://mems1.ni.utoledo.edu/engine">
      <EngineLibVersion>1</EngineLibVersion>
      <EngineBase BaseName="XJGTS">
         <Configuration>
            <SteadyStateSolver SloverName="NewtonRaphsonSolver"
                    ErrorTolerance="5.0E-4" ConvergenceRate="0.7"
                    InterationToFailure="50" PerturbationSize="0.25"
                    LowerPartialLimit="0.0010" UpperPartialLimit="0.01"/>
            <TransientSolver SloverName="ImprovedEuler"
                    ErrorTolerance="5.0E-4" ConvergenceRate="0.7"
                    InterationToFailure="50" DeltaTime="0.2"
                    FinalTime="2.0" PerturbationSize="0.25"
                    LowerPartialLimit="0.0010" UpperPartialLimit="0.01" />
            <Connectors>
               <Connector from="Environment" to="LPC" isFeedback="false"/>
               <Connector from="LPC" to="MV13" isFeedback="false"/>
               <Connector from="MV13" to="HPC" isFeedback="false"/>
               <!-- other connectors are defined in a similar mannar -->
            </Connectors>
        </Configuration>
        <EngineModel>
            <Components>
               <!—only Nozzle is illustrated here, the same with all other components -->
               <NonSource>
                 <NonRatator>
                    <Nozzle Name="Nozzle">
                       <NozzleDesignPointData MassFlowRate="195.0"
                          ThroatArea="430.0" ExitArea="492.0" DragCoefficient="0.952"
                          VelocityCoefficient="0.98" GrossThrust="9400.0"/>
                       <!—the same with NozzleInitPointData-->
                       <ThroatAreaTransientControllers name="Throat Area Transient Controller">
                         <TimeArray> 0.0 10.0 13.0 </TimeArray>
                         <ValueArray> 430.0 430.0 660.0 </ValueArray>
                       </ThroatAreaTransientControllers>
                       <!— the  same with ExitAreaTransientControllers -->
                    </Nozzle>
                 </NonRatator>
               </NonSource>
            </Components>
        </EngineModel>
      </EngineBase>
</EngineRoot>
```

Figure 11. Engine simulation configuration file specified in XML file format


Nozzle data - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Nozzle
Go
Done
My Computer

X-JGTS Simulation Data View

Run by: rin Mon April 03 07:50:00 PST 2002

NozzleDesignPointData

MassFlowRate	ThroatArea	ExitArea	DragCoefficient	VelocityCoefficient	GrossThrust
195.0	430.0	492.0	0.952	0.98	9400.0

NozzleInitialOperatingData

ThroatArea	ExitArea
430.0	492.0

Throat Area Transient Controller

TimeArray	ValueArray
0.0	430.0
10.0	430.0
13.0	660.0

Exit Area Transient Controller

TimeArray	ValueArray
0.0	492.0
10.0	492.0
13.0	880.0

Steady State Solution Data

ThroatArea	ExitArea	VelocityCoef	DragCoefficient	PressureDrag	GrossThrust	MassFlowRate	FuelAirRatio
430.0000	492.0000	0.9564	0.8897	0.0000	1921.31	100.3765	0.00000000

Transient State Solution Data

Time	ThroatArea	ExitArea	VelocityCoef	DragCoefficient	PressureDrag	GrossThrust	MassFlowRate	FuelAirRatio
0.0000	430.0000	492.0000	0.9564	0.8897	0.0000	1921.31	100.3765	0.00000000
0.1000	430.0000	492.0000	0.9554	0.8879	0.0000	1998.39	101.4041	0.00000000
0.2000	430.0000	492.0000	0.9537	0.8848	0.0000	2132.93	102.4534	0.00000000
0.3000	430.0000	492.0000	0.9534	0.8849	0.0000	2256.23	103.4677	0.00000000

Figure 12. Nozzle simulation data displayed within a user's web browser

CONCLUSION

In this work, an XML-based dynamic databinding framework for use in engine simulation has been discussed. By dynamic data binding, the framework provides an object interface to access and use engine data, transparently mapping simulation data in engine components as engine data objects. The framework also enables the separation of engine simulation logic from its persistence logic, such that the engine simulation codes and the underlying data persistence codes can be developed independently.

Since engine component data in the binding process are stored in an XML document, they not only bypass the requirement to have a standard binary encoding or storage format, but also provide the meaning of the data through its tag representation. Furthermore, it is completely natural to move around XML engine data using HTTP through disparate networks.

This paper also describes a Web-based engine simulation system, *X-Jgts*, which internally uses engine databinding framework. The simulation system couples a front-end graphical user interface, developed using the Java Swing API, and various Java Servlet-based web components from engine simulation server to service user's requests. The designed web components include remote simulation service, dynamic data display service in HTML format, and file download and upload services which allow a user to save data for later use in a more secure way. All these services are readily available via the built-in databinding framework support and the use of XML to describe engine data. The combined package provides analytical, graphical and data management tools which allow users to construct and control dynamic gas turbine simulations by manipulating graphical objects from a variety of heterogeneous computer platforms through the use of Java-enabled world-wide web browsers.

The method developed in this paper is generic and may readily be used for other simulation applications requiring intensive data exchange. Using this approach, developers are enabled to design better aircraft engine simulation codes via a systematic and more meaningful data representation scheme and a built-in data validation method.

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Improving the Aircraft Design Process Using Web-based Modeling and Simulation

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Abstract

Designing and developing new aircraft systems is time-consuming and expensive. Computational simulation is a promising means for reducing design cycle times, but requires a flexible software environment capable of integrating advanced multidisciplinary and multifidelity analysis methods, dynamically managing data across heterogeneous computing platforms, and distributing computationally complex tasks. Web-based simulation, with its emphasis on collaborative composition of simulation models, distributed heterogeneous execution, and dynamic multimedia documentation, has the potential to meet these requirements. This paper outlines the current aircraft design process, highlighting its problems and complexities, and presents our vision of an aircraft design process using Web-based modeling and simulation.

1 Introduction

Intensive competition in the commercial aviation industry is placing increasing pressure on aircraft manufacturers to reduce the time, cost and risk of product development. To compete effectively in today's global marketplace, innovative approaches to reducing aircraft design-cycle times are needed. Computational simulation, such as computational fluid dynamics (CFD) and finite element analysis (FEA), has the potential to compress design-cycle times due to the flexibility it provides for rapid and relatively inexpensive evaluation of alternative designs and because it can be used to integrate multidisciplinary analysis earlier in the design process [17]. Unfortunately, bottlenecks caused by data handling, heterogeneous computing environments and geographically separated design teams, continue to restrict the use of these tools. In order to fully realize the potential of computational simulation, improved integration in the overall design process must be made. The opportunity now exists to take advantage of recent developments in information technology to streamline the design process so that information can flow seamlessly between applications, across heterogeneous operating systems, computing architectures programming languages, and data and process representations.

The World Wide Web has emerged as a powerful mechanism for distributing information on a very large scale. In its current form, it provides a simple and effective means for users to search, browse, and retrieve information, as well as to publish their own information. The Web continues to evolve from its limited role as a provider of static document-based information to that of a platform for supporting complex services. Much of this transformation is due to the introduction of object technologies, such as Java and CORBA (Common Object Request Broker Architecture) [36] within the Web. The integration of object technology represents a fundamental (some would say, revolutionary) advancement in web-technology. The web is no longer simply a document access system supported by the somewhat limited protocols. Rather, it is a distributed object system with which one can build general, multi-tiered enterprise intranet and internet applications.

The integration of the Web and object technology enables a fundamentally new approach to simulation: *Web-based simulation*. A Web populated with digital objects — models of physical counterparts — will lead to model development by composition using collaborative Web-based environments [9]. Model execution will occur across networks using Web-based technologies (e.g., Java) and distributed simulation techniques (e.g., CORBA). Finally, simulation execution, models, and other related data will be documented using forms of hypermedia (hypertext, video, virtual models, etc.).

Web-based simulation has the potential to provide the necessary tools to improve the aircraft design process through integration and support for collaborative modeling and distributed model execution. In the remainder of this paper, we examine how this might be achieved. In Section 2, we provide a brief overview of the aircraft design process, drawing attention to the complexities of the process and its inherent problems. Section 3 provides a review of the area of Web-based simulation, and singles out several principles of Web-based simulation that we believe are important in the aircraft design process. In Section 4, we present an example scenario illustrating how Web-based modeling and simulation might be used in that process, and discuss aircraft model development and distribution using the Onyx simulation framework. Onyx's object-oriented component model, visual environment for model assembly, and support for both Web-based and distributed object execution are explained in context of the integration of a jet engine within the aircraft. Lastly, in Section 5, the relationships to the Web-based simulation principles outlined in Section 3 are identified and discussed, as are general implications of Web-based simulation on the design process.

2 The Aircraft Design Process

The aircraft design process can be divided into three phases: *conceptual design*, *preliminary design*, and *detailed design*. The conceptual design phase identifies the various conditions of the mission, and synthesizes a set of initial aircraft configurations capable of performing the mission. For commercial aircraft, the mission is defined by airline company demands, which typically include payload requirements, city-to-city distance along a proposed service route, traffic volume and frequency, and airport compatibility. If the conceptual design effort confirms the feasibility of the proposed mission. management may decide to proceed with one or more preliminary designs. In the preliminary design phase, more detail is added to the aircraft design definition. Here the aerodynamic shape, structural skeleton and propulsion system design are refined sufficiently so that detailed performance estimates can be made and guaranteed to potential customers. In the final design phase, the airframe structure and associated sub-systems, such as control systems, landing gear, electrical and hydraulic systems, and cabin layout, are defined in complete detail [17].

The design of an aircraft is an inherently complex process. Traditional preliminary design procedure decomposes the aircraft into isolated components (airframe, propulsion system, control system, etc.) and focuses attention on the individual disciplines (fluid dynamic, heat transfer, acoustics, etc.) which affect their performance. The normal approach is to perform disciplinary analysis in a sequential manner where one discipline uses the results of the preceding analysis (see Fig. 1). In the development of commercial aircraft, aerodynamic analysis of the airframe is the first step in the preliminary design process. Using the initial Computer-aided Design (CAD) geometry definitions resulting from the conceptual design studies, aerodynamic predictions of wing and fuselage lift and drag are computed. Key points in the flight envelope, including take-off and normal cruise, are evaluated to form a map of aerodynamic performance. Next, performance estimates of the aircraft's propulsion system are made, including thrust and fuel consumption rate. The structural analysis uses estimates of aerodynamic loads to determine the airframe's structural skeleton, which provides an estimate of the structure weight.

Complicating the design process is the fact that each of the disciplines interacts to various degrees with the other disciplines in the minor analysis loop. For example, the thrust requirements of the propulsion system will be dependent on the aerodynamic drag estimates for take-off, climb and cruise. The values of aerodynamic lift and yaw moments affect the sizing of the horizontal and vertical tail, which in turn influence the design of the control system. For an efficient design process, fully-updated data from one discipline must be made accessible to the other disciplines without loss of information. Failure to identify interactions between disciplines early in the minor design cycle can result in serious problems for highly integrated aircraft designs. If the coupling is not identified until the system has been built and tested experimentally, then the system must undergo another major cycle iteration, further increasing the time and expense of product development.

There are many factors that can make the design process less efficient. These include:

(1) *Lack of interoperability.* Numerous software packages — CAD, solid modeling, FEA, CFD, visualization, and optimization — are employed to synthesize and evaluate designs. These tools are often use different, possibly proprietary, data formats. As a result, they generally do not interoperate, and require manual manipulation when passing data between applications. Although in some cases, custom translation tools are available to "massage" the data into the appropriate format, users still spend considerable time and effort tracking data and results as well as preparing, submitting and running the computer applications [28].

(2) *Heterogeneous computing environments.* The aircraft design computing environment is extremely heterogeneous, with platforms ranging from personal computers, to Unix workstations, to supercomputers. To use the various software required in the design process, users are forced to become familiar with different computer architectures, operating systems and programming languages.

(3) *Geographically separated design groups.* Multidisciplinary design and analysis is frequently carried out by geographically dispersed engineering groups. In special cases, entire subsystems may be designed and developed by third-party contractors or companies. The propulsion sub-system, for example, is designed and built separately by the propulsion company, and delivered to the aircraft company for installation in the aircraft. In any case, geographic separation places pressure on the designers to maintain a high level of interaction during the design process so that loss of data is minimized.

Improving the design process, therefore, requires the development of an integrated software environment which provides interoperability standards so that information can flow seamlessly across heterogeneous machines, computing platforms, programming languages, and data and process representations. We believe that web-based simulation tools can provide such an environment.

3 Principles of Web-based Simulation

Since its inception in 1990, the World Wide Web (WWW or Web) has quickly emerged as a powerful tool for connecting people and information on a global scale. Built on broadly accepted protocols, the WWW removes incompatibilities between computer systems, resulting in an "explosion of accessibility" [2, 30]. Within the simulation community this proliferation has led to the establishment of a new area of research — *Web-based simulation* — involving the exploration of the connections between the WWW and the field of simulation. Although the majority of work in web-based simulation to date has centered on re-implementation of existing distributed and standalone simulation software using Web-related technologies, there is growing acknowledgement that web-based simulation has the potential to fundamentally alter the practice of simulation [11].

In one of the first papers to explore the topic of web-based simulation, Fishwick [8] identifies many potential effects of web-based simulation, with attention given to three key simulation areas: (1) education and training, (2) publications, and (3) simulation programs. He concludes that there is great uncertainty in the area of Web-based simulation, but advises simulation researchers and practitioners to move forward to incorporate Web-based technologies. Building on Fishwick's observations, Page and Opper [25] present six principles of web-based simulation which capture the vision of future simulation practice: (1) digital object proliferation, (2) software standards proliferation, (3) model construction by composition, (4) increased use of "trial and error" approaches, (5) proliferation of simulation use by non-experts, and (6) multi-tier architectures and multi-language systems.

In the remainder of this section, we briefly review several of these principles. In the following sections, we will examine in more detail how each apply to both the development of a simulation environment, and to the improvement of the aircraft design process.

3.1 Digital Objects.

In the mid 1960's a pioneering simulation language called Simula-67 [3] was developed to more faithfully model objects in the physical world. Simula-67 introduced many of the core design concepts (e.g., classes and objects) which form the foundation for the object-oriented programming paradigm. Since that time, object-oriented technologies, such as object-oriented programming (OOP), design (OOD) and analysis (OOA), have had a major impact on the field of simulation. Today, the majority of simulation languages, as well as many of the most successful general purpose-languages, are object-oriented.

The importance of objects in simulation applications naturally leads us to consider their use as part of the WWW infrastructure. The WWW, however, is currently based on documents, rather than objects. In the future, though, it is envisioned that the Web will be populated by digital objects, with documents being just one type of object. The objects, representing models and data for use in simulation environments, will be made available for use through publication on the WWW [9].

Indications of a transition to an object-based WWW are currently evident in the successful application of *mobile code* and *distributed object* technologies. Mobile code — programs which can be transmitted across a network and executed on the client's computer — make it possible to deliver digital objects, in either executable or serialized form across the WWW. Several programming languages which can produce mobile code have been developed [4, 32, 33, 34]; the most well known and widely supported is Java [1]. Compiled Java code, known as byte-code, can be downloaded across the Web to the client where it is executed by a Java Virtual Machine. The Java run-time system, incorporated within the Java Virtual Machine, provides an extensive class library that can be accessed by the compiled code.

Component Object Model (COM) [29], and High Level Architecture (HLA) [21]. Alternatively, a component architecture may be defined by the particular simulation application in which the objects are to operate. This is often the case in domain-specific simulation environments, where the component architecture must be crafted to meet specific requirements of the domain. The Onyx simulation environment, described in the following section, is such an example; it defines a component architecture which is oriented towards physical modeling of aerospace systems.

3.4 Heterogeneous Modeling and Simulation

The digital objects of our Web-based simulation future will populate a Web that is highly heterogeneous. Digital objects will certainly be developed using different programming languages and programming styles (e.g., object-oriented, procedural, functional, etc.). The digital objects will themselves be highly variable. Some will be based on mobile code which can move across the Web (e.g., agents), while others will form object busses which provide services from specific locations on the Web. Applications will become more complicated as a result, with complex multi-tier architectures becoming the standard. In order to operate effectively in such an environment, Web-based simulation will need extensive enabling technologies such as search engines to locate appropriate digital objects and models, translators to convert models and data to appropriate formats, and expert systems to guide non-experts in the use of Web-based simulation models.

4 An Example Scenario

In this section, we present a scenario illustrating how Web-based modeling and simulation can be used in the aircraft design process. Our goal is to discuss both the technical issues related to the design, development and publication of digital objects, as well as organizational issues concerning the roles engineers and programmers play in the Web-based design process. Although the discussion is oriented towards the aircraft design process, we believe that it is applicable to engineering processes used in many fields.

4.1 Onyx

The modeling and simulation environment for our research is the *Onyx* simulation system [26, 27]. The major features of Onyx include the following.

- A set of object classes and interfaces for representing the physical attributes and topology of the aircraft system is included. These classes comprise an object-oriented *component architecture* capable of housing the analytical and geometric views of the various aircraft components employed in the design process. The architecture facilitates and ensures object interoperability among separately developed software components.
- A *visual assembly interface* is included for graphical creation and manipulation of aircraft system models. It enables users to establish model design, control model execution and visualize simulation output.
- A dynamically-defined, run-time *simulation executive* is included to control complex, multi-level simulations.
- A *persistence engine* capable of transparently accessing geometry and data stored in either relational or object database management systems is included.
- A *connection service* provides access to federated model and data repositories using standard internet protocols. Various connection strategies to access Web- and server-based distributed objects are included.

Our goal in creating Onyx is to develop a simulation-based design system that promotes collaboration among aerospace designers and facilitates sharing of models, data and code. Special emphasis is placed on developing a distributed system which fosters reuse and extension in both the models and the simulation environment. To achieve these goals, we have made extensive use of object-oriented technologies such as *object-oriented frameworks*, *software components*, and *design patterns*.

An object-oriented framework is a set of classes that embodies an abstract design for solutions to a family of related problems [19]. Onyx is designed as a layered collection of frameworks, with individual frameworks for the visual assembly interface, persistence engine, connection services, simulation executive and component architecture. The set of classes in each framework define a "semi-complete" structure that captures the general functionality of the application or domain. Specific functionality is added to Onyx by inheriting from, or composing with, framework components. In the example in the next section, we will illustrate this by deriving new classes to represent the components in an aircraft engine, then assembling instances of those classes to form a complete engine model.

A key characteristic of Onyx, and object-oriented frameworks in general, is its inverted control structure. In traditional software development, the application developer writes the main body of the application which defines a series of calls to various libraries of subroutines. These libraries provide reusable code, while the main body is customized by the application developer. In framework design, the control structure is defined by the framework, with predefined calls going to methods that the application developer writes. In this approach, the design or structure of the application — which is domain-specific — is reused, and the specific functionality of the application is provided by the developer. Using this approach, Onyx reduces the burden for aircraft engineers and modelers, allowing similar aircraft component models to be developed faster and more efficiently. The concept of reuse is best illustrated for models that are assembled from a library of components (i.e., composition), and for models that are made in several versions with minor differences (i.e., inheritance).

A major product of object-oriented design is the identification of software components — self contained software elements which can be controlled dynamically and assembled to form applications. The central step in identifying them is recognizing recurring fundamental abstractions in the domain. By identifying these abstractions and standardizing their interfaces, these components become interchangeable. Such components are said to be "plug-compatible" as they permit components to be "plugged" into frameworks without redesign. Onyx's software components use a variant of the JavaBeans [7] component architecture to define standard interfaces and abstractions. These components represent the "plug-compatible, digital objects" with which the Web-based models of the aircraft and its subsystems are developed.

Throughout the Onyx environment, design patterns — recurring solutions to problems that arise when building software in various domains [13] — are used to achieve reuse. Patterns aid the development of reusable software components and frameworks by expressing the structure and collaboration of participants in a software architecture at a level higher than source code or object-oriented design models that focus on individual objects and classes [31]. Patterns also are particularly useful for documenting software architectures and design abstractions. They provide a common and concise vocabulary which is useful in conveying the purpose of a given software design.

The Onyx simulation environment is designed to be both multi-tiered and platform independent so as to provide the greatest flexibility when modeling complex aircraft systems. Java was chosen as the implementation language as it offers extensive class libraries, a distributed object model (i.e., Java RMI), and byte-code interpreters on a wide range of computer architectures, among other benefits. As a result, the Onyx system is extremely portable and accessible. The visual assembly interface (described below), for example, can be run in the context of a Web browser, which are widely available, while computationally intensive components run on dedicated, distributed servers.

Java is also the preferred language for programming Onyx software components, as models written in Java are easily downloaded across a network and dynamically loaded into the Onyx environment. In cases where it is desirable or necessary to use a programming language other than Java, software components may be accessed from Onyx using CORBA. CORBA's ability to deal with the heterogeneous nature inherent in distributed computing environments makes it particularly suitable for leveraging legacy applications not written in Java. This is especially useful for simulation of aerospace systems in which the majority of existing analysis programs have been written in procedural languages, such as FORTRAN and C. The use of CORBA adds flexibility to the Onyx system allowing it to "wrap" these existing programs, rather than having to replace or abandon them.

4.2 Engine-Aircraft Integration Scenario

This scenario illustrates our vision of how Web-based modeling and simulation may be used in the process of development and integration of an aircraft subsystem within the complete aircraft. As stated earlier, the aircraft design process generally follows a hierarchical decomposition of the aircraft system (see Fig. 2a) into major airframe components, e.g., Fuselage, Rudder, Wing and Propulsion System (i.e., Engines). Individual engineering groups are responsible for establishing the conceptual and preliminary designs for each respective component. These teams work together, exchanging information as necessary, to develop the individual component designs, and as the process progresses, to integrate them into a final design.

We have selected for our example the integration of the propulsion subsystem into the aircraft because it represents one of the more complex aspects of aircraft design. Propulsion system performance, size and weight are important factors in the overall aircraft design. Engine size and thrust, for example, influence the number and placement of engines, which in turn affects aircraft safety, performance, drag, control and maintainability. Furthermore, because the engine is designed and developed by an external manufacturer — i.e., an engine company — this example illustrates the challenges faced by designers separated both geographically and organizationally. We intend to show how Web-based modeling and simulation can address these and other issues.

4.2.1 Model Authoring. As in the aircraft company, engineering design groups in the engine manufacturer are generally organized according to a physical decomposition of the engine, with individual teams responsible for developing the major engine components: Fan, Compressor, Combustor, Turbine, Mixer, etc. (see Fig. 2b). In each team, a *model author*, having expertise in the given design area, establishes a conceptual model of the component. During early phases of design, model resolution is kept relatively coarse to speed simulations and enable more complete exploration of the design space. Such a model typically consists of a set of algebraic and/or linearized ordinary differential equations which describe the component's gross behavior. At this stage in the design knowledge of component characteristics is incomplete, so empirical data gathered from rig-testing of previously developed components are scaled to approximate the current model. These data, commonly referred to as "performance maps," attempt to capture component characteristics within their operating range, and serve to provide closure to the equations.

4.2.2 Component Authoring. Once a conceptual model is validated, a *component author*, working closely with the model author, maps the model to the computational domain, creating a software component which encapsulates the model abstraction. As pointed out in section 3, the mapping is largely dependent on the choice of component architecture being used. The Onyx component architecture used here is based upon a *control volume* abstraction. The use of control volumes is standard engineering practice, wherein the physical system is divided into discrete regions of space — control volumes — which are then analyzed by applying conservation laws (e.g., mass, momentum, energy) to yield a set of mathematical equations describing physical behavior (see Fig. 3). A component architecture predicated on this approach provides a convenient and familiar mapping mechanism for modeling physical systems, and ensures that a simulation component resembles the conceptual model developed by the model author. A brief overview of the Onyx component architecture is presented below; a complete description can be found in ref. [26].

4.2.3 Overview of Onyx Component Architecture. There are four basic entities in the Onyx architecture: *Element*, *Port*, *Connector* and *DomainModel* (see Fig. 4). The Java interface Element represents a control volume, and defines the key behavior for all engineering component classes incorporated into Onyx. It declares the core methods needed to initialize, run and stop model execution, as well as methods for managing attached Port objects. Classes implementing this interface generally represent physical components, such as a compressor, turbine blade, or bearing, to name a few (see Fig. 3b). However, they may also represent purely mathematical abstractions such as a cell in a finite-volume mesh used in a CFD analysis. This flexibility permits the component architecture to model a variety of physical systems.

Consider, for example, a component author in the Compressor design team wanting to develop a representative Compressor digital object for use in simulations during preliminary design. The author begins by defining a concrete implementation of the **Element** interface, such as **SimpleCompressor** (see Fig. 4). Here the author extends the abstract class **DefaultElement**, which captures common implementation aspects of the **Element** interface, as well as maintaining a list of **Port** objects associated with its subclasses. Alternatively, the author could implement the interface directly, explicitly defining each interface method. This feature is used through the architecture to provide flexibility: the component author may select to utilize the default functionality of the common abstract class, or inherit from another class hierarchy and implement the interface directly.

An **Element** may have zero or more **Port** objects associated with it. The interface **Port** represent a surface on a control volume (i.e., **Element**) through which some entity (e.g., mass or energy) or information passes. **Ports** are generally classified by the entity being transported across the control surface. For example, the **SimpleCompressor** has two **FluidPort** objects — representing the fluid boundaries at the Compressor entrance and exit — and a **StructuralPort** object, representing the control surface on the Compressor through which mechanical energy is passed (i.e., from a driving shaft). The **Port** interface defines two methods to set and retrieve the data defined by the Port. These data may be stored in any type of Java Object, such as **Hashtable** or **Vector**. The common abstract class, **DefaultPort**, defines default functionality for these methods, and maintains a reference to the **Connector** object currently connected to the **Port**.

The common boundary between consecutive control volumes is represented by a **Connector** object. The interface **Connector** permits two **Element** objects to communicate by passing information between connected **Port** objects (see Fig. 3c). It is also responsible for data transformation and mapping in situations where the data being passed from **Ports** of different type. The need for such data transformation can range from simple situations, such as conversion of data units, to very complex ones involving a mismatch in model fidelity (e.g., connecting a 2-D fluid model to a 3-D fluid model) or disciplinary coupling (e.g, mapping structural analysis results from a finite-element mesh to a finite-volume mesh used for aerodynamic analysis).

For all but the simplest cases, the algorithms needed to perform the data transformation/ mapping will tend to be very complex. To improve reusability, Connector delegates transformation/mapping responsibilities to a separate Transform object (see Fig. 3c) which encapsulates the necessary intelligence to expand/contract data and map data across disciplines. The Transform interface (see Fig 4) defines a general method, transform, which is implemented by subclasses to carry out a particular transformation algorithm.

A similar situation is found with the mathematical model used to define component behavior. As described above, the mathematical models used to describe Compressor (or any other component) behavior during preliminary design are relatively simple and may be solved analytically or using basic numerical methods. However, models used in latter phases of design can be quite complicated. In these cases, approximate solutions are obtained by discretization of the equations on a geometrical mesh and applying highly specialized numerical solvers. The presence of these complex mathematical models and the numerical tools needed to solve them suggest that it is desirable to encapsulate these features and remove them from the Element structure. This enhances the modularity of Element, allowing new Element classes to be added without regard to the mathematical model used, and conversely to add new models without affecting the Element class. To achieve this, Onyx utilizes the Strategy design pattern [13] to encapsulate the mathematical model in a separate type of object called DomainModel (see Fig. 4). The benefit of this pattern is that families of similar algorithms become interchangeable, allowing the algorithm — in this case the DomainModel — to vary independently from the Elements that use it. This admits the possibility of run-time selection of an appropriate DomainModel for a given Element; however, this is currently not used in Onyx. Furthermore, encapsulating the DomainModel in a separate object also encourages the “wrapping” of pre-existing, external software packages. For example, the Fan DomainModel in Fig. 3d might “wrap” a three-dimensional (3-D) Navier-Stokes or Euler flow solver to provide steady-state aerodynamic analysis of fluid flow within the Fan. This approach allows proven functionality of existing software analysis packages to be easily integrated within an Element. Some of the advantages of this concept is illustrated later in this section.

The **DomainModel** interface is designed to be very general, due to the complicated nature of the various models which might be encapsulated in an **Element**. The intent is not to restrict the use of any algorithm or the "wrapping" of external software packages by overly defining the **DomainModel** interface. Consequently, the interface defines only two methods, execute and halt, which are used to start and stop the execution of the **DomainModel** code. Additional methods are obviously needed to access and make the data internal to the **DomainModel** available to the **Element**, but because these are specific to the particular **DomainModel** structure, they are not included in the interface. For our example, the component author has defined a **SimpleCompressorModel** class (see Fig. 4) to encapsulate the set of ordinary differential equations and performance maps needed to model compressor behavior.

After the Compressor class definitions (i.e., **SimpleCompressor**, **FluidPort**, **StructuralPort** and **SimpleCompressorDomainModel**) are established, the component author compiles, verifies and tests their operation. When complete, the class' byte-code files and any auxiliary data (e.g., performance maps) are combined to form a single Compressor software component in the form of a Java Archive (JAR) file. The JAR file format is useful for encapsulating components as they can be compressed to reduce file size, digitally signed for added security, and easily transferred across the Web.

4.2.4 Publishing the Component. The Compressor software component is "published" by deploying it on a Web server where it can be accessed by others in the engine company. We envision that each engine component design team will maintain its own Web server, hosting the software components it has developed (see Figure 5). However, it may be easier and more efficient to maintain all components on a single company-wide Web server. In either case, publishing the software component is the responsibility of the *component deployer*, who has expertise in system and Web server administration. This expertise is necessary, since, in addition to simply placing components on a Web server, the component deployer is responsible for addressing server configuration issues of component identification and security.

***4.2.5 Accessing Components*.** One of the problems facing a user of a Web-based simulation system is locating appropriate software components, objects or data, for use in a simulation. A text-based search engine, similar to those used on the Web today, is one possible method to find objects and components [9]. However, these tools suffer from the fact that they are oriented towards HTML documents, rather than objects. A more object-oriented approach is to use *naming* and *directory* services to catalog available simulation objects and components. Using a naming service, the component deployer associates names with objects, providing the means to look up an object given its name. CORBA and RMI are examples of distributed object systems that employ naming services. Directory services extend naming services by adding attributes, making it possible to search for objects given their attributes. These attributes may be used by the component deployer to describe and hierarchically organize each component. For example, the attributes may be specified which describe the component class name, model fidelity and discipline, model author, or version number, as well as the manufacturer's name and component group, to name a few. Queries can be made to the directory service to find and return references to objects matching one or more attributes. Lightweight Directory Access Protocol (LDAP) [38] and NetWare Directory Service (NDS) [23] are examples of directory services which are used today.

Another important responsibility of the component deployer is establishing and maintaining security policies controlling access to published software components. These components represent significant investments in both time and money for the manufacturer. To protect their intellectual property against theft through reverse engineering, it is important to ensure that relevant data and software components can only be accessed by authorized users. Protection is accomplished through the use of *authentication* and *authorization* mechanisms. Authentication refers to the presence of an authentication protocol (e.g., password, Kerberos ticket [24],or public key certificate (X.509 [16], PGP [39], etc.) that identifies the requesting party (the principle), while authorization grants access only if the principles identity (credentials) is included in a specific list (the access control list), or if the principle can assume a specific role (role-based authorization). Both authentication and authorization mechanisms are typically included as part of the naming and directory services, or as part of the Web server services. Using these mechanisms, the component deployer can control who gains access to the server, and what data can be read.

Communication channels between a client and the Web server are also a source of security concern. If the communication channel is a dedicated network connection (i.e., intranet or extranet), security problems are minimized due to physical isolation. If, however, the communication channel is the Web, physical isolation is impossible, and encryption mechanisms, such as Secure Socket Layers (SSL) [15], must be used.

4.2.6 Building the Engine. Once the engine component design teams publish their preliminary component objects, a *system integrator*, having expertise in system-level engine design. combines individual component objects to create a first-order engine model. The system-level engine model is developed using Onyx's visual assembly interface. Icons, representing individual engine components (i.e., Elements), are selected from a *component browser*, dragged into a workspace window, and interconnected to form a schematic diagram (see Fig. 6).

The component browser, as its name implies, is a tool for browsing the objects and data stored in a naming or directory service (see bottom-right corner of Fig. 6). Onyx currently supports access to common naming and directory services, such as NDS, LDAP, CORBA Naming Service (COS Naming), and RMI Registry, through the Java Naming and Directory Interface (JNDI) [18]. JNDI is an API that provides an abstraction that represents elements common to the most widely available naming and directory services. JNDI also allows different services to be linked to together to form a single logical namespace called a *federated* naming service. Using the component browser, Onyx users are ale to navigate across multiple naming and directory services to locate simulation data, objects and components.

For security purposes, the component browser requires users to authenticate themselves before they can retrieve any information from a naming or directory service. Once authentication has been successfully completed, the user can browse or search (using attribute keywords) the entire namespace (subject to any authorization restrictions). Authentication and authorization capabilities are provided through JNDI and the Java Authentication and Authorization Service (JAAS) [22] framework. These tools allow the component browser to remain independent from the underlying security services, which is an important concern when working in a heterogeneous computing environment such as the Web.

Dragging an icon from the component browser to the workspace window causes the selected software component to be downloaded from the server to the client machine. Components comprised entirely of Java classes, such as the Compressor described above, are downloaded from a Web server to the local file system where the byte-codes are extracted from the JAR file, loaded into the Java Virtual Machine and instantiated for use in Onyx. Components developed in other programming languages are not downloaded, but remain on the server. Instead, a proxy object (stub), representing the component, is downloaded and used to connect to the remote component using a distributed object service, such as RMI, Voyager [37], CORBA, or DCOM. The need to use remote components in the aircraft design process is discussed at the end of this section.

Onyx supports the creation of hierarchical component models, and an icon can represent both a single component or an assembly of components. A component with subcomponents is called a *composite* or *structured* component. Components that are not structured are called *primitive* components, since they are typically defined in terms of primitives such as variables and equations. Composite components are represented by the **CompositeElement** class, which is part of the **Element** hierarchy (see Fig. 4). The class structure, based on the Composite design pattern [13], effectively captures the part-whole hierarchical structure of the component models, and allows the uniform treatment of both individual objects and compositions of objects. Such treatment is essential for providing the object interoperability needed to perform Web-based model construction by composition.

Figure 6 shows a composite model representing an aircraft turbofan engine. The icon labeled Core is a composite of components which are displayed in the lower schematic. Each icon has one or more small boxes on its perimeter to represent its **Ports**. Connecting lines are drawn between the ports on different icons by dragging the mouse. A Connector object having the correct Transform object needed to connect the two ports is created automatically by Onyx. Each icon has a popup menu which can be used "customize" the attributes of its Element, Port and DomainModel objects. When selected, a graphical Customizer object is displayed (see upper-right corner of Fig. 6), which can be used to view or edit the selected objects attributes. The visual assembly interface also provides tools for plotting (see the lower-left corner of Fig. 6), editing files, and browsing on-line documentation. More information on the design and implementation of the visual assembly interface can be found in ref. [26].

4.2.7 ***Engine-Aircraft Model Integration***. The system integrator, working with the model and component authors, performs a series of simulations to evaluate and improve the performance of the first-order engine model. Component conceptual models are refined and new software components developed, deployed and integrated, until all preliminary engine design requirements are satisfied. The engine model is then "passed" to engineers in the aircraft design group for use in their design process. This is accomplished by publishing the engine model as a CompositeElement object in the same process as described above, except that the engine component is deployed on a Web server accessible from networked locations outside the engine company (i.e., extranet). In the aircraft company, airframe designers use the preliminary engine component (now a sub-component in the airframe system model) to design the control system, size the airframe and design the planform (see Fig 5). An *aircraft* system integrator takes the engine component and, using the Onyx visual assembly interface, assembles an airframe model using components (e.g., rudder, fuselage, and wing) developed by aircraft design groups (see Fig. 6) in a process similar to the one described for the Compressor component. This model can then be used to simulate gross aircraft performance.

4.2.8 Hierarchical Models. While the preliminary engine component is being used by the aircraft design teams, the engine component teams continue to refine their designs. The refinement requires sophisticated models which give a detailed description of the underlying physical processes within the component. For instance, although the air flow through the

Compressor might be adequately modeled as a quasi-one-dimensional, inviscid fluid in early phases of design, the actual fluid flow is unsteady, three-dimensional (3-D) and characterized by turbulence, boundary-layers and shocks. Similarly, at an early stage of design the Compressor blades can be modeled as rigid, but for more detailed investigations it may be necessary to account for blade deformation due to material elasticity and thermal loading. Thus, simulating the behavior of complex components requires the development of a hierarchy of models, or *multimodel*, which represent the component at differing levels of abstraction [10]. These models may include: lumped-parameter models, such as the one used to model the Compressor component in preliminary design, or distributed parameter models such as fluid dynamics (CFD) or structural mechanics (FEA). Each model is implemented using a numerical method best suited to the application; e.g., an ordinary differential equation solver (ODE) for state-space models, finite-element solvers for structural mechanics or finite-volume solver for fluid dynamics. The specific numerical method implementation is encapsulated within the model. Figure 2c shows a multimodel representing the Compressor blade and flowfield at differing levels of fidelity. At the lowest level of fidelity, both the blade and flowfield are modeled using simple differential equations and empirical data. At higher fidelities, both are modeled using sophisticated numerical methods such as finite element analysis or computational fluid dynamics.

4.2.9 High-fidelity Distributed Components. The use of multimodels in Web-based modeling and simulation is important because it allows designers to selectively refine the fidelity of their model given the constraints (i.e., level of detail needed, the objective, the available knowledge, given resources, etc.) of the simulation. However, digital objects containing higher-fidelity models cannot be deployed in the same manner as the simple models described previously. High-fidelity CFD and FEA software packages are (generally) not written in Java, and thus cannot be run in the clients Java virtual machine. Even if this were possible, the packages are computationally intensive, making them unsuitable for execution on the client computer. Therefore, high-fidelity models are deployed as remote objects using distributed object services such as CORBA. This approach offers several advantages:

(1) Ability to distribute a computationally intensive process across a number of processors
(2) Ability to leverage legacy code limited to platforms offering specific programming and/or operating systems by "wrapping" it in a remote object
(3) Specialization of computer execution environment (i.e., placement of codes on appropriate computing platforms: such as visualization codes on high-end graphic workstations; computationally intensive codes on supercomputers, etc.).

As with the preliminary component models, the high-fidelity component models can be integrated into a system-level engine model by the engine system integrator, and used to simulate engine operation. An engine simulation using a model composed of high-fidelity components would provide detailed knowledge of the interaction effects between its components. Although these interactions can be critical to engine performance, they are not currently quantifiable by engine designers and therefore are unknown until after expensive hardware testing [5, 14]. Evaluation of these effects will allow engine engineers to make better design decisions earlier in the design process, before the principle design features have been frozen. Each high-fidelity component would perform its computations using a wrapped analysis package located on one or more remote computers. For example, in Fig. 5, the Fan component is run on a supercomputer, while a parallel software package is used to simulate Compressor operation using a cluster of computers.

The high-fidelity engine model is also a valuable resource to aircraft designers, and once the model is published, can be used in the aircraft model. The engine model allows aircraft designers to investigate the flowfield around aircraft nacelle (the cowling structure around the engine) and fuselage. Detailed descriptions of flow features at the engine exit (e.g., shocks and expansion waves), could allow aircraft designers to better predict the drag caused by the jet exhaust flowing along the aircraft surface. Engine designers would also benefit from a high-fidelity, integrated engine-aircraft simulation. For example, an integrated simulation could allow engine designers to study distortions in the airflow entering the engine when the aircraft is at a high angle of attack. Evaluation of this operating condition is important because distortions can cause the compressor to stall and the engine to lose thrust. A detailed engine-aircraft integration study would provide valuable information which engine and aircraft engineers could use to better and more quickly design the aircraft.

5 Concluding Remarks

The design of complex systems involves the work of many specialists in various disciplines, each dependent on the work of other groups. When a single designer or core team is able to control the entire design process, difficulties in communication and organization are minimized. However, as design problems become more complex, the number and size of disciplinary groups increases, and it becomes more difficult for a central group to manage the process. As the design process becomes more decentralized, communications requirements become more severe. These difficulties are particularly evident in the design of aircraft, a process that involves complex analyses, many disciplines, and a large design space [20]. The lack of enabling software supporting disciplinary analysis by geographically dispersed engineering groups further aggravates these problems.

In this paper we have argued that Web-based simulation has the potential to improve the aircraft design process, allowing companies to become more competitive through condensed cycle times and better products. This improvement is due, in part, to the ability of the Web to support collaborative modeling and distributed model execution in a heterogeneous computing environment. A central focus of this strategy is the move towards a Web based on digital objects which can be published and reused to form new models.

Using a component architecture such as the one defined in the Onyx environment, digital objects can be developed which represent the hierarchical topology of physical systems, making them ideal as models of aircraft systems. Furthermore, these objects can encapsulate multimodels, including geometry models, multidisciplinary models and models having multiple levels of fidelity. Such models are ideal for concurrent design environments, since all of the modeling information is available in one place. The component architecture class structure provides the capability to wrap existing software packages. This is extremely important in providing collaborative and integrative environment for the aircraft design process.

A World-Wide Web populated with digital objects provides the foundation for modeling by composition. Onyx's component architecture defines the standard interfaces needed to dynamically compose new objects and the visual assembly interface makes composition simple and easy. This promotes model reuse, as well as reducing new model development time.

The Onyx environment supports the distribution of simulation models across the Web. Both Web-based model distribution (in the case of Java-based models) and distributed services approaches (e.g., CORBA, COM) are provided. Each of these increase Onyx's usability, as models can be placed virtually anywhere. The CORBA bindings make it possible to integrate non-Java language distributed objects and legacy code. Also, since Onyx is written entirely in Java, it is portable without modifications to any computing platform which supports the Java Virtual Machine. Heterogeneous computing support makes the Onyx Web-based simulation system extremely viable for use in the heterogeneous computing environments typical of aircraft companies. Most importantly, it allows access to existing legacy codes and access to codes which must operate on specific architectures or operating systems.

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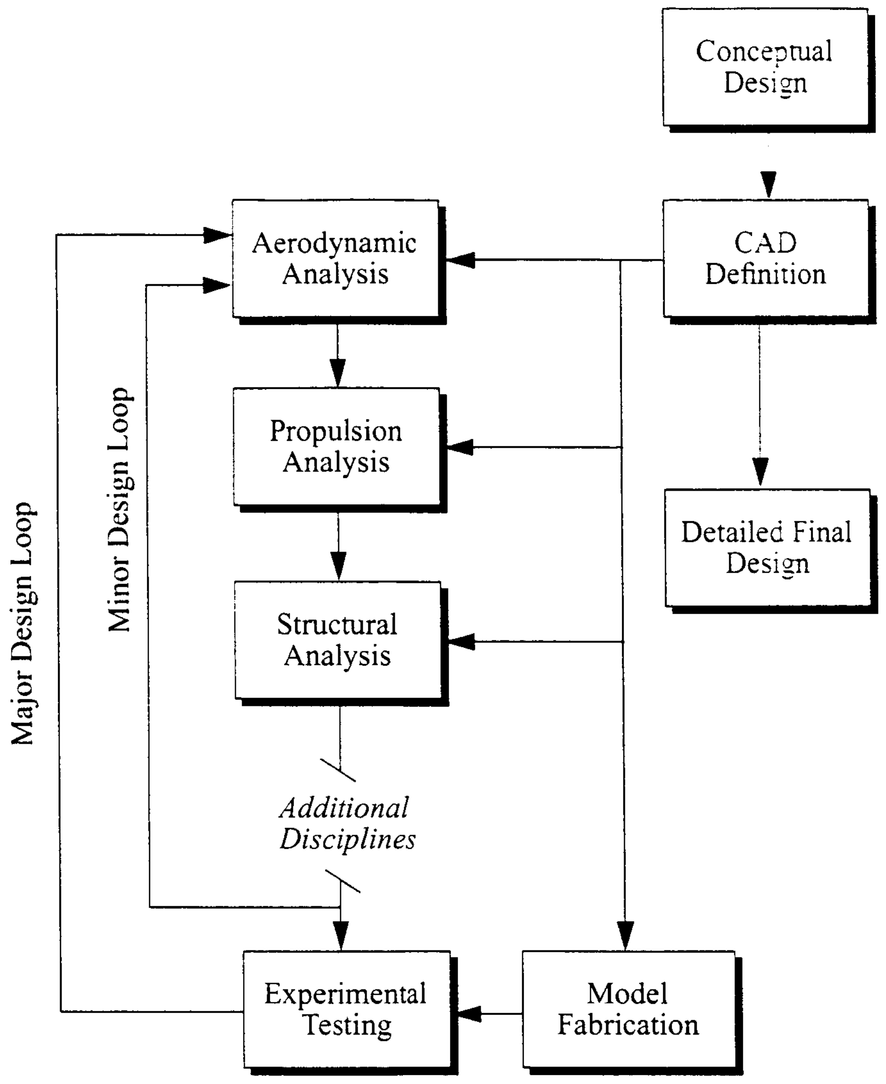


Figure 1: The Aircraft Design Process. The process involves conceptual, preliminary and detailed final design phases. The preliminary design phase includes both major and minor design loops. In the minor design loop, separate disciplinary analysis such as aerodynamic, propulsion, and structural analysis are carried out. Additional disciplinary analysis, such as controls, loading, stability, acoustics, etc. have been omitted for clarity. Once a design is converged upon in the minor loop, it is experimentally tested in the major design loop. After convergence of the major design loop, the detailed final design phase is executed.

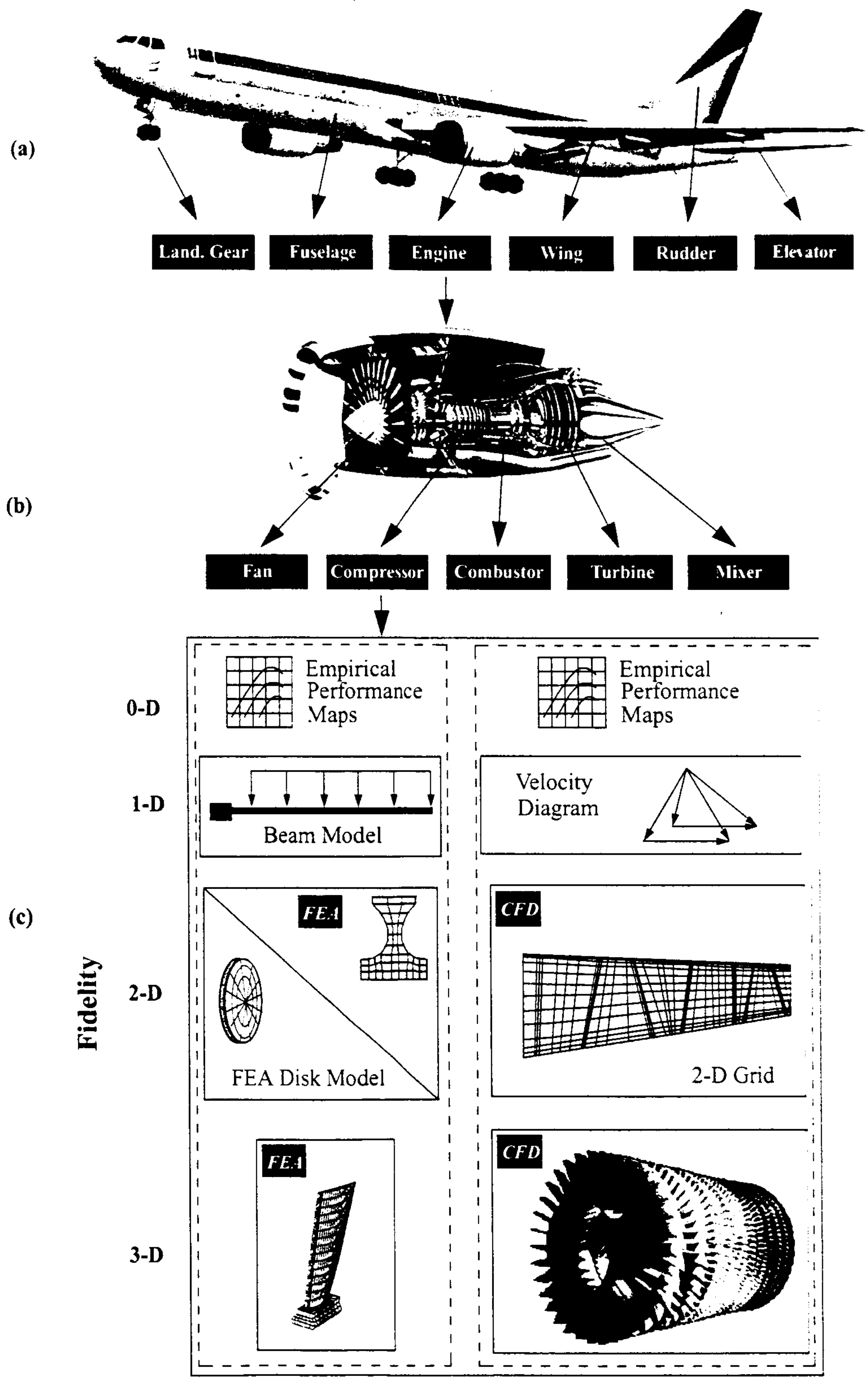


Figure 2: (a) Decomposition of aircraft into high-level components; (b) decomposition of engine component; and (c) collection of models (multimodels) at differing levels of fidelity and discipline for Compressor component.

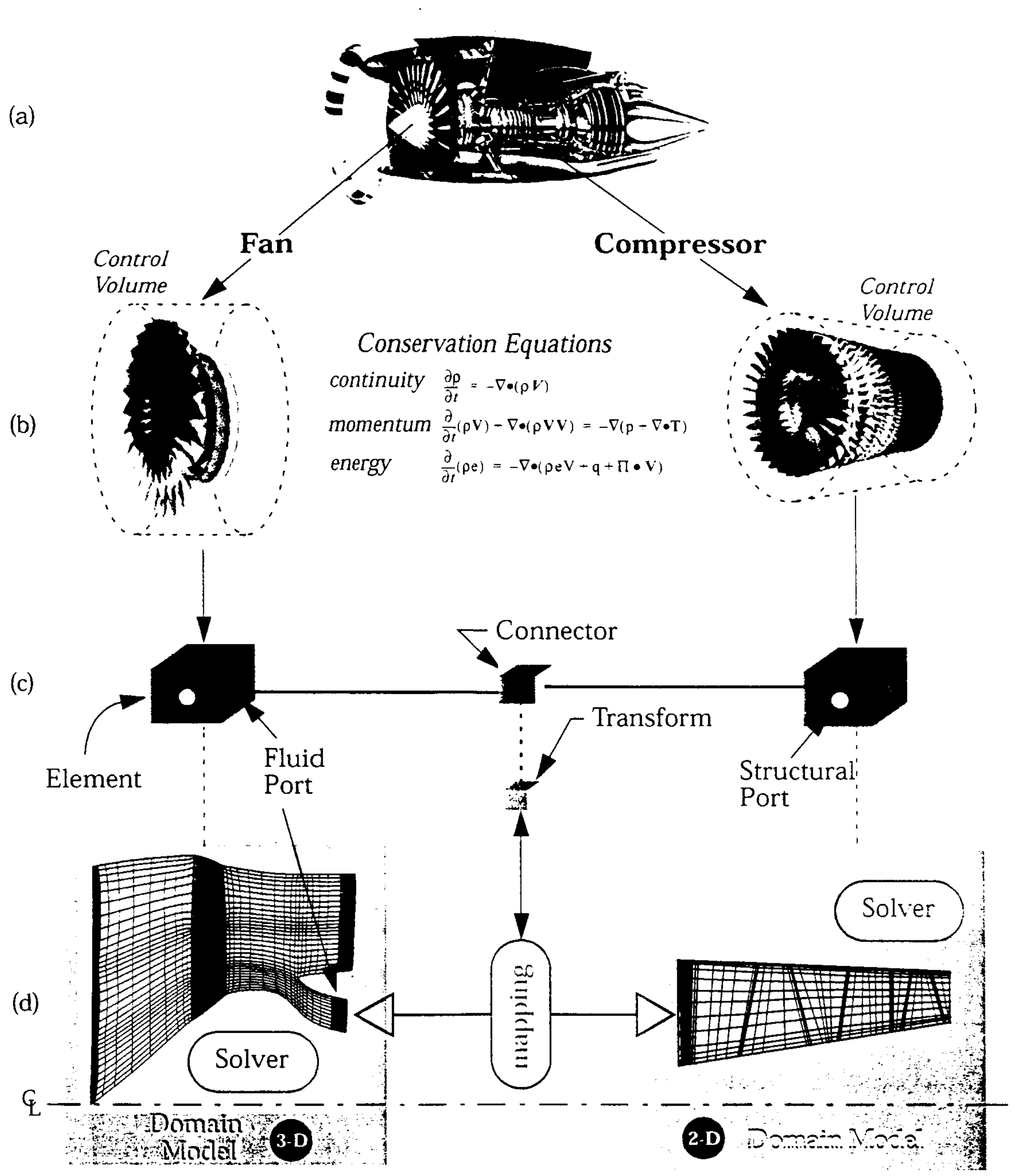

(a)
Fan
Compressor
Control Volume
Control Volume
(b)
Conservation Equations
continuity $\frac{\partial \rho}{\partial t} = -\nabla \bullet (\rho V)$
momentum $\frac{\partial}{\partial t}(\rho V) - \nabla \bullet (\rho V V) = -\nabla (p - \nabla \bullet T)$
energy $\frac{\partial}{\partial t}(\rho e) = -\nabla \bullet (\rho e V - q + \Pi \bullet V)$
(c)
Connector
Transform
Element
Fluid Port
Structural Port
(d)
Solver
mapping
Solver
℄
Domain Model 3-D
2-D Domain Model

Figure 3: Mapping of engine physical domain to computational framework. (a) Engine is decomposed into separate components, such as the Fan and Compressor. Component control volumes are defined (b), with behavior defined by conservation laws. Components are represented in Onyx as **Elements** (c), whose **Ports** are connected by **Connectors**. Component behavior is defined by a **DomainModel** (d) which may apply numerical discretization methods to solve the conservation equations. Data exchange at control volume boundaries is passed via **Ports** and **Connectors**, with multifidelity and interdisciplinary mapping handled by **Transform** objects.

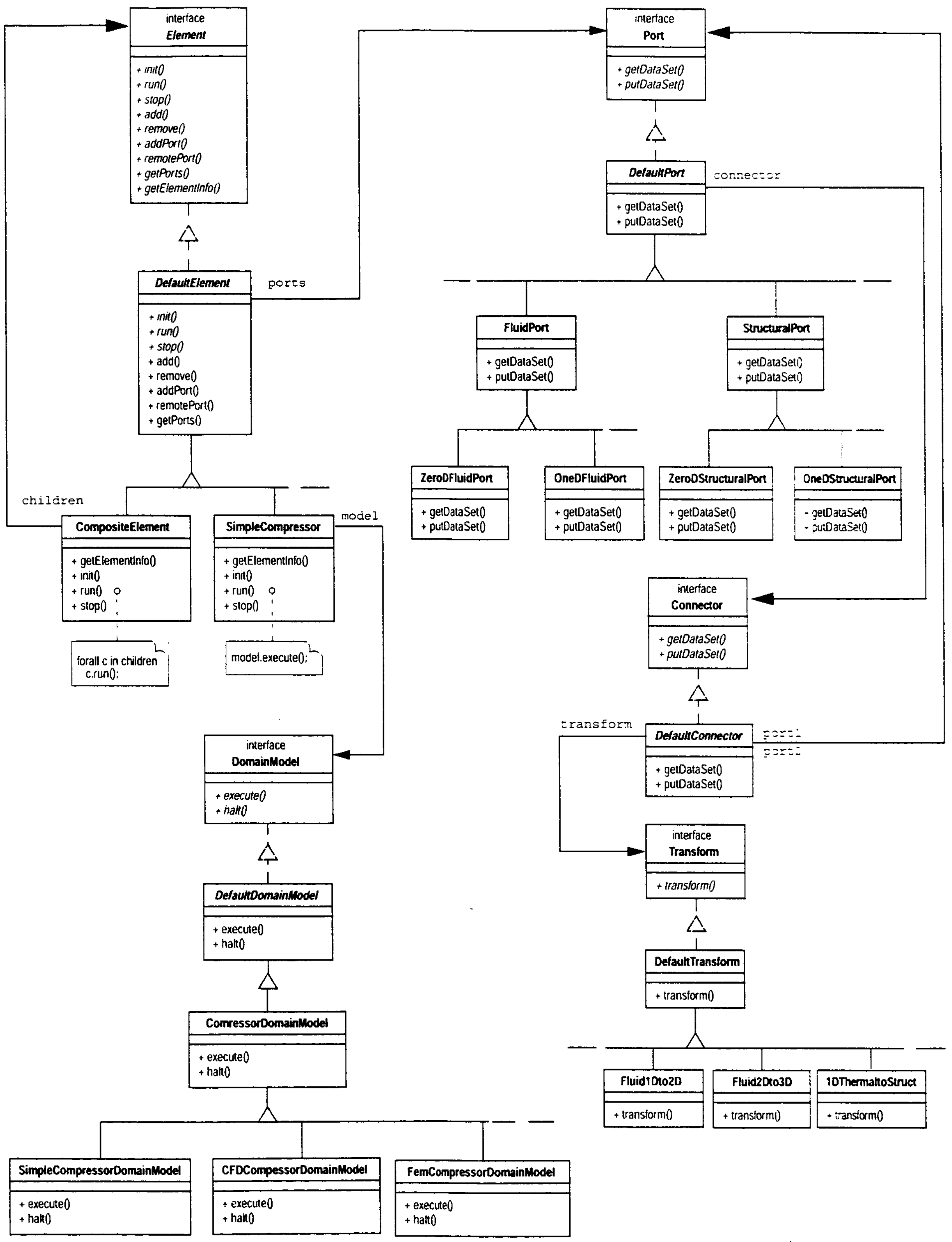


Figure 4: A portion of the Onyx component architecture class structure.

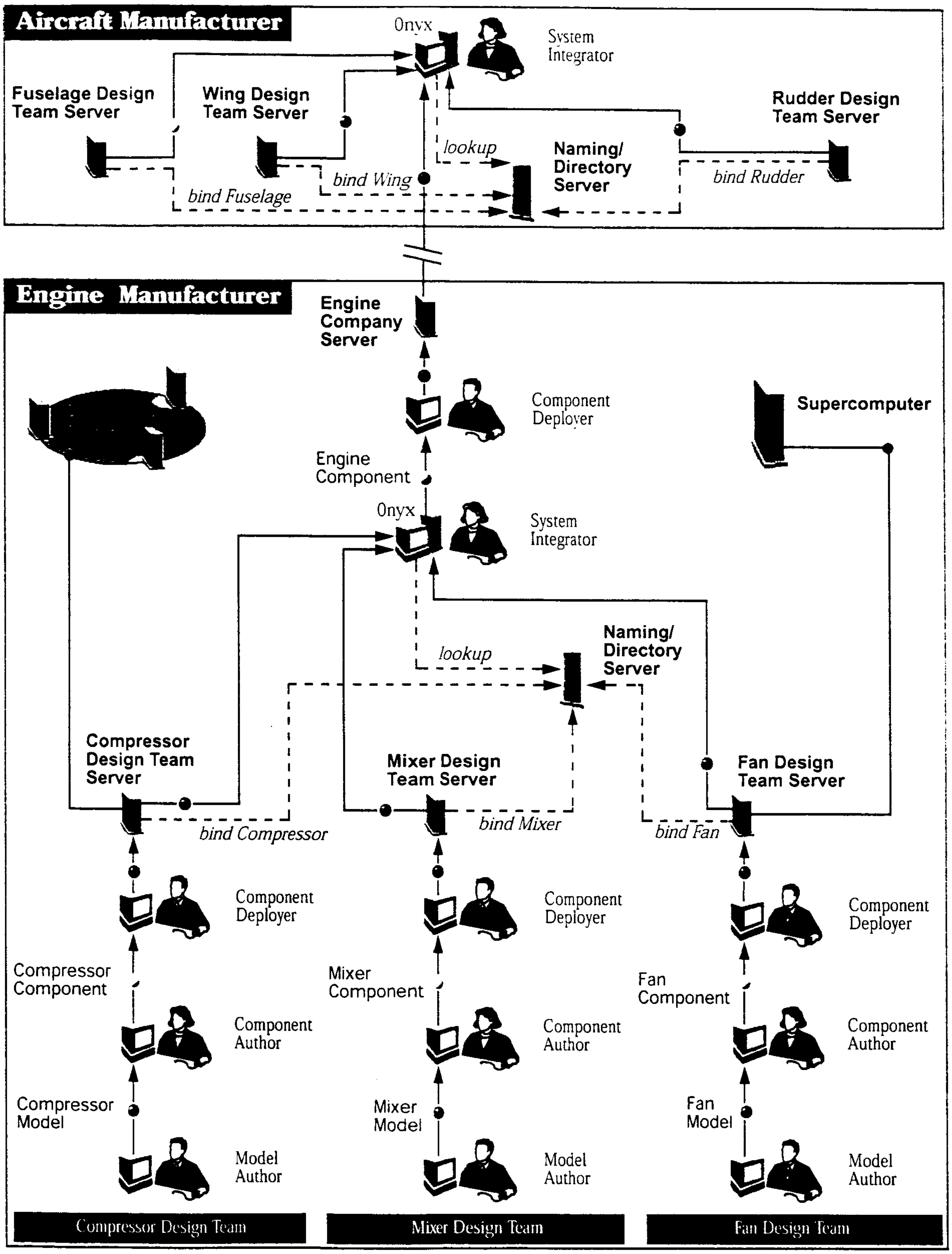
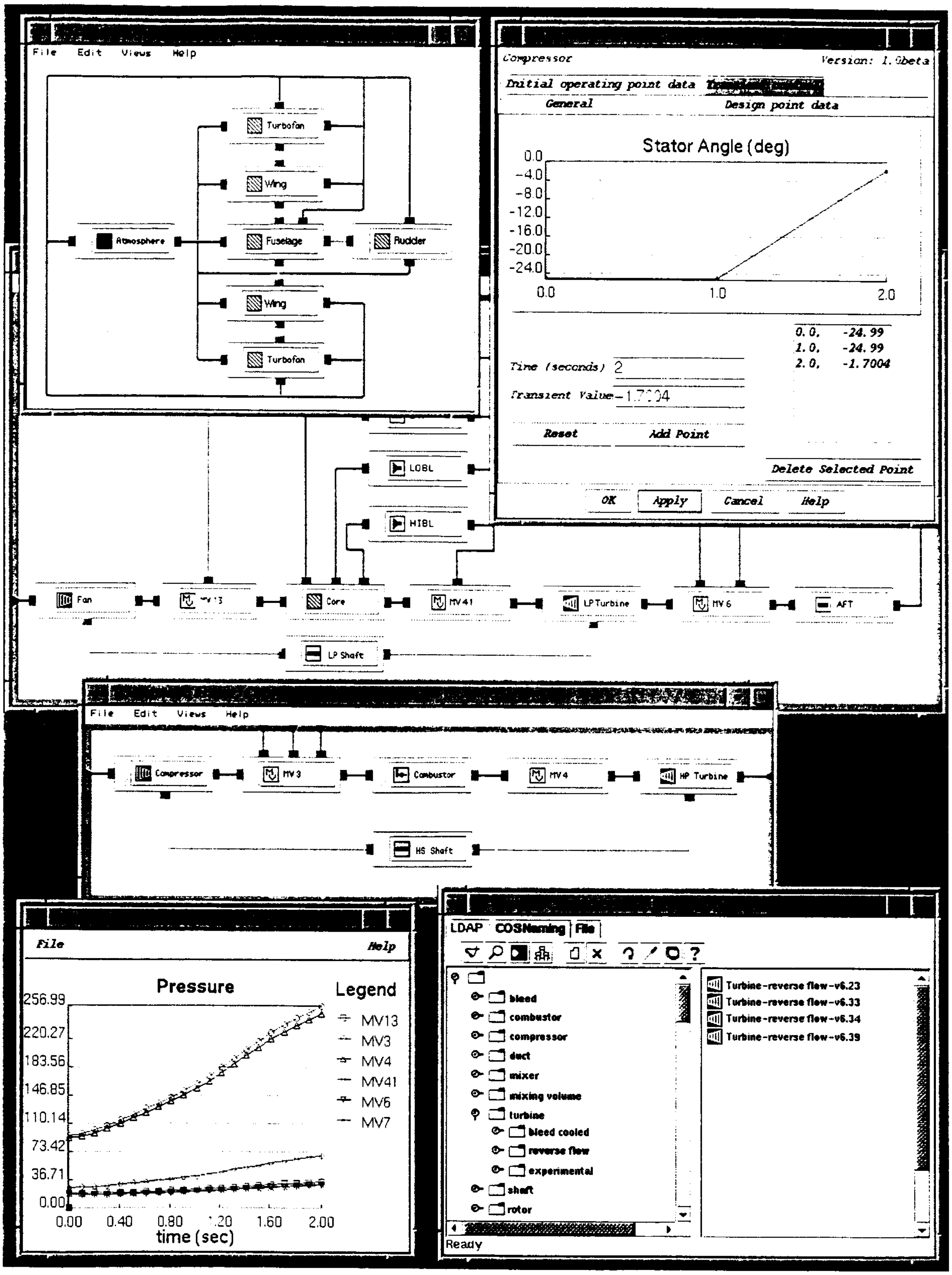


Figure 5: Exchange of digital objects in a Web-based simulation environment.



0.0,	-24.99
1.0,	-24.99
2.0,	-1.7004

Figure 6: Overview of Onyx Visual Assembly Interface.