# Bio-inspired Fault Tolerant and Adaptive System Modeling and Simulation on the Grid

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## Abstract

*Grid computing, which is characterized as large-scale distributed resources sharing and cooperation, is becoming a mainstream technology in distributed computing. In this paper, we present the idea of applying grid-computing technology to model and simulate large-scale and high-performance bio-inspired fault tolerant and adaptable control system. Grid-based workflow management service is employed to cooperate various grid services and organizations for modeling and simulating the process of designing the bio-inspired control system. The large-scale processing capability of the grid helps to establish the grid-based distributed sensory system model inspired by a biological neuron. The multi-organization collaboration facility of the grid is used to implement the fault detection and prevention model inspired by the defense mechanism of a biological body. The tremendous amount of sharing computational resource in the grid enable us to perform large-scale simulation of reconfigurable and adaptive strategy inspired by the self-healing capability of biological systems. The grid-computing infrastructure of modeling and simulating the bio-inspired control system in large scale is expected to lead to a deeper understanding of system mechanism and then a more advanced design of the modern control system.*

## 1. Introduction

The ability to tolerate hardware failures and adapt to dynamically changing environment is essential for safe and reliable operation of dynamic systems. Systems must be protected from a variety of potential faults. A common solution is through the use of redundancy where critical modules are replicated by a number of the same modules. The conventional fault tolerance approaches have many shortcomings: they cannot tolerate unpredictable failures, nor do they fit in a changing environment easily. On the other hand, biological systems exhibit capabilities of adapting to new environment, handling uncertainty, and collaborating with other biological systems. Such systems also have sophisticated protecting, learning, and repairing (self-healing) mechanisms. One possible solution to achieve high-level system fault tolerance is to draw inspiration from nature and incorporate biological-like characteristics to control systems.

Bio-inspired systems are "man-made systems whose architectures and emergent behaviors resemble the structure and behavior of biological organisms." [1] Recent years have seen radically different models and methods of bio-inspired reliable and adaptive systems, such as Bio-inspired Systems Information Processing [2], Fault Diagnosis for Power Distribution Systems [3], Bio-Networking Architecture [4], Biologically-Inspired Integrated Sensors [5], and Bio-inspired Robust Engineering [6]. Computational simulation is carried out as a fundamental tool to assist model design, algorithm analysis, and system performance assessment. Nevertheless, due to the complication of modern control system and its operating environment, modeling and simulating bio-inspired adaptive and reconfigurable systems experiences the following complications:

- Heavy load of computation: Simulating bio-inspired control system and its operating environment behaviors is a computation-intensive task. Modeling and simulation tasks, such as fault detection, fault identification, search for optimal reconfiguration, and uncertainty simulation, require large amount of computational CPU cycles. Thus, the bio-inspired control system simulation favors large-scale parallel or distributed computing.
- Large-scale of dataset: The simulation of bio-inspired control system requires large amount of data. At the same time, the system will also produce large amount of data. Large-scale data sharing is required for various simulation modules. Simulation performing on parallel or distributed system requires data communication in large volume as well. In this sense, the simulation application is also data-intensive.
- Module collaboration: Bio-inspired control systems exhibit complex logic and the system design demands involvement of various functional modules, including sensors, knowledge database, decision modules, and actuators. Modeling and simulating bio-inspired control system require collaboration and interaction among various modules in different domains.

In a word, a large-scale and cost-effective computing infrastructure is the key to effectively modeling and simulating a bio-inspired control system.

Grid computing [7] is an emerging technique to support on-demand "virtual organizations" for distributed resource sharing and problem solving on a global scale for data-intensive and computation-intensive applications. In the grid-computing environment, the large-scale computational resources, the global-wide networking connectivity, the accessibility to experimental instruments, the participation of scientists and engineers in different areas, and the coordination of organizations make the grid-computing environment an ideal platform to execute large-scale bio-inspired control system simulation applications. Nevertheless, despite the attractive characteristics of grid computing, the grid environment presents a number of new challenges [8]:

- Cross-domain: The lack of ownership and control results in misinterpreting information and other uncertain factors.
- Dynamism: The goal of bio-inspired adaptive system simulation is to test the system performance in a changing environment. The simulation of the operating environment requires the underlying grid agents to be able to adjust their behaviors.
- Heterogeneity: The resources in a grid-computing environment are from various organizations, having different hardware architectures, running various operation systems and applications, and communicating via different protocols.

Although the characteristics of grid computing make it a natural fit for modeling and simulating large-scale bio-inspired control system, manageable and reliable infrastructure for the grid-computing environment is required. The workflow management services [9, 10] on the grid are designed to efficiently manage and organize the grid resources for scientific computation. The extensive markup language, XML [11], is fast becoming a standard for data interchange on the grid.

In this paper, we present a grid-computing infrastructure for large-scale and high-performance bio-inspired control system modeling and simulation. The gird workflow management technique based on XML is used to manage the modeling and simulation process.

The remainder of this paper is organized as follows. In Section 2, we analyze grid-based workflow, including grid workflow components, decomposition of a grid workflow, description of grid-based workflow in XML, and dynamic grid workflow service. Section 3 shows the grid-based modeling and simulation of bio-inspired control system, including the distributed sensory system, the fault detection and prevention mechanism, and the reconfigurable and adaptive strategy. Finally, Section 4 summarizes our conclusions and future research directions.

## 2. Workflow and the Grid

### 2.1 Grid-based Workflow

Originally, workflow is an administrative concept from the field of managing business operation, referring to a business process that delivers services from one participant agent to another. In 1996, getting its definition from the Workflow Management Coalition, a workflow is described as [9]:

> *The automation of a business process, in whole or part, during which documents, information or tasks are passed from one participant to another for action, according to a set of procedural rules.*

The emergence of workflow introduces the automated process, which enforces the data validation and verification within business operations, overcomes constraints in time and space, maintains consistency in the business system, and significantly eliminates possible human errors. Workflow is making important contributions to many types of business. Nevertheless, the concept of workflow extends beyond its use in conventional business process management, and is used more broadly in e-science, e-commerce, and other areas.

Recently, the development of the Internet computing provides networking connectivity services all over the world. More importantly, the emergence of grid computing, which is characterized as "large-scale cooperation and sharing of dynamical distributed resources," [7] supplies tremendous amount of computational resources and services, and formalizes a way for cooperation of different organizations. The services in the grid-computing environment include networking connectivity services, computational services, storage services, information services, and security services. The Open Grid Service Architecture (OGSA) [8] allows the distributed resources to be shared over a network and the existing grid services to cooperate. Moreover, the development of grid-computing middleware, such as the grid-enabled relational database access [14], the grid-based messaging system [15], the grid security infrastructure [16], and the grid-based infrastructure for Monte Carlo applications [17, 18], provides higher-level functionalities in high-performance and reliability for large-scale complicated computational application, such as the modeling and simulation of bio-inspired control system.

The dynamic nature of large-scale scientific computing application requires more "flexible" agents and services in grid organizations to be based on dynamic ontology. To meet this requirement, the grid-based workflow services are designed to be capable of handling "plug-and-play" computations. Moreover, the grid-based workflow services combine various grid services together to generate more complex services to implement more complicated operations.

### 2.2 Components in a Grid Workflow

Workflows need many capabilities, and as mentioned in "e-science gap analysis" [10], four key components are highlighted to describe a workflow:

- Composition/Development: To provide an IDE to virtually form the graph of workflow.
- Language and Programs: To describe the workflow using a formal language.
- Compiler: To translate the above two steps into the executable form.
- Enactment Engines: To support the execution of the workflow in the execution environment.

These four components correspond to related capabilities in a conventional programming environment.

### 2.3 Decomposing a Grid Workflow

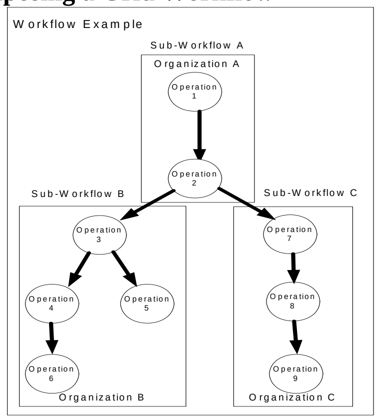


Figure 2: Grid Workflow, Sub-workflows, and Operations

A scientific computing task on the grid is composed of a number of subtasks. The corresponding workflow on the grid can be decomposed into smaller units [13]. These units can be described as follows:

- Operation: Operations are the smallest elements in a grid workflow. Each operation is usually carried out on a grid node.
- Sub-workflow: A sub-workflow is a flow of closely related operations that is to be executed in a predefined order on the grid resources within a virtual organization. Each sub-workflow represents a specific scientific computing subtask in an organization. Sub-workflows may be executed in parallel.
- Workflow: A workflow can be represented as a flow of several loosely coupled activity described in a scientific computing process. Each activity consumes various grid resources and can be represented by a sub-workflow.

The grid workflow management service schedules sub-workflows in a workflow to the target organizations. Then, operations are executed on the grid resources in the organization. Figure 2 shows an example of a grid workflow diagram.

### 2.4 XML Describing a Grid Workflow

XML is fast becoming the standard for data interchange on the grid due to its well-defined syntax and platform independency. Therefore, XML is used as the primary message format for communications within grid services. In fact, an XML document is an information container for reusable and customizable components, which can be used by any receiving services. The services in a workflow may use an XML format to explain their "problems," defining new performatives in terms of existing, mutually understood ones. Based on the commonly agreed tags, services in a workflow may use different style XML DTDs (Document Type Definition) to fit the taste of the business units they mediate. Therefore, XML is widely used to address the heterogeneity issue in grid computing and to enable cross-domain cooperation among grid services.

Figure 3 shows the XML describing the workflow example in Figure 2. The workflow is decomposed into three sub-workflows. Each sub-workflow is to be scheduled on a grid organization specified by the "organization" tag. The "order" tag indicates the execution order of these sub-workflows. The "operation" tag carries out the "problem description" of the current operation, including the application-specified actions and requested grid resources.

```
<WorkFlow id = “mainworkflow”>
  <SubWorkFlow id = “subworkflow1”, order = 1>
    <Organization id = “organizationA”> </Organization>
    <DataTransfer> … </DataTransfer>
    <Operation> description of operation 1 and 2</Operation>
    <DataTransfer> … </DataTransfer>
  </SubWorkFlow>
  <SubWorkFlow id = “subworkflow2”, order = 2>
    <Organization id = “organizationB”> </Organization>
    <DataTransfer> … </DataTransfer>
    <Operation> description of operation 3, 4, 5, 6 </Operation>
    <DataTransfer> … </DataTransfer>
  </SubWorkFlow>
  <SubWorkFlow id = “subworkflow3”, order = 2>
    <Organization id = “organizationC”> </Organization>
    <DataTransfer> … </DataTransfer>
    <Operation> description of operation 7,8,9 </Operation>
    <DataTransfer> … </DataTransfer>
  </SubWorkFlow>
</WorkFlow>
```

Figure 3. XML Describing Grid Workflow Example Shown in Figure 2

### 2.5 Dynamic Workflow Services on the Grid

Among the components in a grid-based workflow described in Section 2.2, the implementation of the workflow enactment engine is one of the more complicated pieces. The enactment engine has the functionalities of workflow management, which are responsible for binding the workflow expression to the actual grid-service components and setting up the necessary inter-service communication registrations. Based on the "problem description" of the operation in the workflow, it picks up appropriate and available grid services, schedules the operations to the grid resources, executes the workflow operation, and collects the operation results.

An enactment engine usually does not have a fixed set of predefined functions, but instead, it carries application-specific actions, which can be loaded and modified on the fly. This allows a grid node running the workflow service using the enactment engine to adjust its capability and play different roles to accommodate changes in the grid organization environment and business requirements. Figure 4 shows the architecture of a workflow service using an enactment engine.

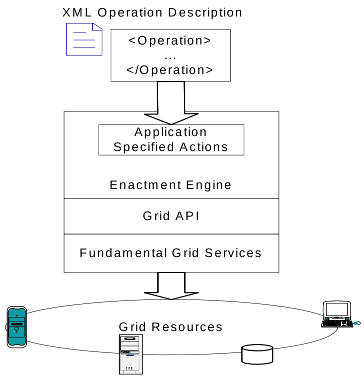


Figure 4: Architecture of a Grid Agent Providing Workflow Service using an Enactment Engine

An agent providing workflow service in the grid-computing environment utilizes the underlying management grid facilities including distributed communication, object storage, database access, job schedule, GUI, and grid resource management. The fundamental grid services enable the workflow agent to carry data, knowledge, and objects, and execute the programs. The data and control logics described in XML form its adaptable part. Their application-specific behaviors are obtained from the workflow process, which enable the agent to perform high-level business operations. Based on these application-specific data, the workflow agent is capable of allocating appropriate grid resources and then processes the corresponding operations specified in the workflow.

### 2.6 Cooperation of Grid Workflow Services with Plug-in Workflow Support

Workflow systems provide flow control for scientific computing process automation. A scientific computing application, such as the simulation of a bio-inspired control system in a complicated and dynamic environment, often involves multilevel collaborative operations. Each operation represents a computational piece of work that contributes to the computing process.

Scientific computing processes may be considered as a kind of multi-agent cooperation, in the sense that a grid workflow agent or a group of grid workflow agents can be used to perform an operation in a workflow, and workflow can be used to orchestrate or control the interactions between the grid services or agents. Multiple grid services or agents working cooperatively may accomplish a particular part of the workflow process, such as a single data processing operation. When an operation is complete in a grid workflow agent, based on the workflow description carried in XML, the workflow control logic and data will be passed to the next workflow agent for the computational operation at next step. Therefore, multiple grid workflow services can cooperate to provide plug-in workflow support.

## 3. Modeling and Simulating Bio-Inspired Systems on the Grid

In this section, we will discuss large-scale modeling and simulating bio-inspired control system on the grid, including the distributed sensory system, the fault detection and prevention mechanism, and the reconfigurable control system. The distributed sensory system requires large-scale data processing capability; the modeling of fault detection and prevention mechanism demands multi-layer collaboration; the simulation of reconfigurable strategy favors large-scale computational resources. This section will show how the coordination of the grid services and the collaboration of the grid resources in grid workflows can meet these requirements.

### 3.1 Distributed Sensory System

On-line monitoring of the control system is essential for its healthy operation. The distributed sensory system is responsible of monitoring the control system. In the sensory hierarchy, highly sensitive heterogeneous sensors are widely distributed in high density and sending raw data. The raw data is in large volume and thus simplifications and refinements are required. The goal of the bio-inspired distributed sensory system is to turn raw data into critical information and detect evolving damage in critical structures [20].

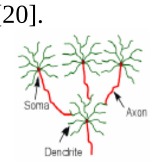


Figure 4: Biological Neuron of Nervous System

The grid-based model of the distributed sensory system takes advantage of the capability of large-scale data processing in grid-computing environment. Figure 4 shows a typical neuron of nervous system. Figure 5 illustrates the grid-based workflow correspondent to the model of the equivalent distributed sensory system. The raw data generated by heterogeneous sensors are usually in different formats. Similar to an axon, the grid nodes providing filtering services produce filtered and well-formatted data in XML based on their built-in analysis and signal processing functions. The grid workflow then evolves. The grid data refining services, which are equivalent to dendrites in a neuron, are embedded into the workflow. They correlates the data streams and produce further refined data for the central processor. With the evolvement of the grid workflow and the collaboration of grid signal processing services inspired by the functionality of a biological neutron, the raw data are filtered and refined to produce meaningful information for next level of the control system.

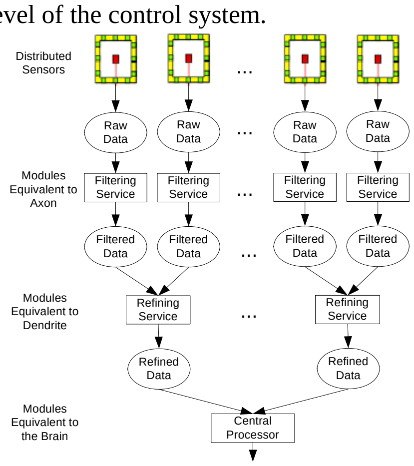


Figure 5: Grid Model of Distributed Sensory System

### 3.2 Fault Detection and Prevention Mechanism

Biology uses numerous approaches to maintain good working operation of the body. If one line of defense is breached, the next uses a different approach. Figure 5 shows the layers of defense mechanisms in the body. The outermost layer is the atomic layer, providing a physical barrier to infection. The next layer creates physiological using elements such as temperature and acidity. The phagocytic layer uses roaming scavenger cells that sweep the body clean of easily detectable foreign microorganisms by engulfing them. The inner acquired immune layer creates its defense mechanisms using the thymus. [21]

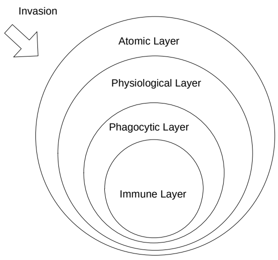


Figure 5: Layers of Defense Mechanisms in the body

A multilayer fault detection and prevention mechanism is inspired by the process of self-nonself discrimination used to detect and prevent bacterial infections in the body is created. Different layers implement different strategies to detect and prevent faults. At the physical layer, a control system can be encased in screened enclosures to provide physical protection and electromagnetic interference reduction. Similar to the physiological layer, environmental controls are used to monitor and stabilize the operating environment of the control system. N-modular redundancy is used to simulate the phagocytic layers. Embryonics and immunotronics approaches are applied to implement artificial immune systems [22].

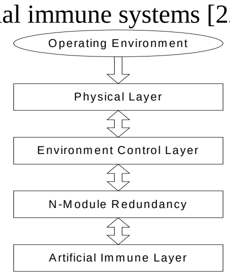


Figure 6: Grid-based Workflow of the Multi-Layer Fault Detection and Prevention System

Figure 6 shows the simulation of grid-based fault detection and prevention system. Each layer is regarded as a virtual organization. The virtual organization collaborates its grid services to embed in the grid workflow to implement its unique fault detection and prevention strategy. The interaction between layers is implemented by the cooperation of the correspondent virtual organizations. In the fault detection and prevention mechanism simulation, the multi-organization collaboration facilities in grid computing are fully used.

### 3.3 Adaptive and Reconfigurable Control Strategy

Biological systems exhibit high reliability because of their self-diagnosis and self-healing mechanism. Inspired by the biological features of adaptation, a reconfigurable and adaptive control strategy [23] is designed to tolerate possible faults and uncertainties. Large-scale simulation is preferred to validate and assess the developed bio-inspired adaptive and reconfigurable models and strategies. Due to the complication of the operating environment, the accurate simulation of the adaptive and reconfigurable strategy favors large amount of computational resources. The tremendous amount of sharing computational resources in a grid-computing environment becomes a nature fit for the simulation requirement.

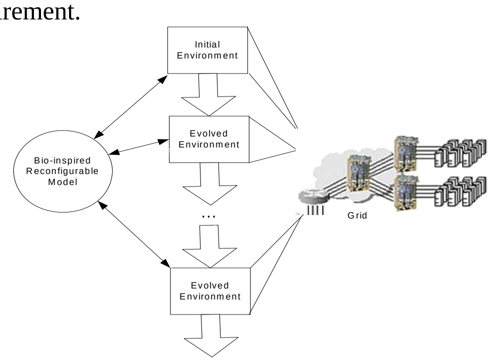


Figure 7: Simulation of Adaptive and Reconfigurable Control System on the Grid

Figure 7 shows the adaptive and reconfigurable control system simulation on the grid. By coordinating the grid services and their large-scale computational resources, the complex operating environment of the control system is simulated. The operating environment evolves with uncertainty implemented by a random process. The bio-inspired reconfigurable model interacts with the virtual environment. Different reconfiguration models can be plugged in the grid-based simulation workflow to validate their adaptability in the changing virtual operating environment. Techniques such as the N-out-of-M scheduling and partial result validation [17] can be applied to improve the performance and reliability of the simulation computation.

## 4. Conclusions

Modeling and simulating a complex bio-inspired fault tolerant control system is a dynamic process requiring heavy computation, large amount of data processing, and module collaboration. In this paper, we present the idea of implementing a grid-computing infrastructure for large-scale and high-performance bio-inspired control system modeling and simulation. Workflow management and XML technique are used to coordinate "plug-in" grid services and resources to carry out modeling and simulation process. Moreover, we investigate in the distributed sensory system, the fault detection and prevention mechanism, and the reconfigurable and adaptive strategy using the bio-inspired approaches. The modeling and simulation of these systems have requirements of large-scale data processing, multi-organization collaboration, and large amount of computational resources, respectively. We show that the grid techniques can be used efficiently and effectively to meet all these requirements.

Nevertheless, more practical and theoretical works still need to be done in this area to address the other issues including security, privacy control, trustworthiness, scalability, and availability of modeling and simulating complex bio-inspired control system on the grid. These will become our next phase of our research. More aggressively, we plan to develop a grid workflow portal – a state-of-the-art approach to design and validate bio-inspired control systems.

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