Peta-Flow Computing: Vision and Challenges

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Abstract

This paper discusses vision and challenges toward realization of peta-flow computing, *which enables peta-scale information processing and communication. A promising application for peta-flow computing, a large-scale upper airway flow simulation and visualization over a long-fat network, is discussed with its requirements on peta-flow computing. Also, challenges and implications of three technological fields of peta-flow computing —* peta-scale computing, peta-scale networking, *and* peta-scale interfacing *are identified.*

1 Introduction

In recent years, because of the advancement of computing technologies represented by large-scale computing, and the rapid growth and deployment of networking technologies represented by the Internet technologies, the amount of information handled has been increasing exponentially. The advancement of conventional cluster computers and the emergence of new computing paradigms such as Grid computing [3] and Cloud computing have been gradually enhancing the scalability of distributed computing. On the contrary, rapid deployment of optical networking technologies such as WDM (Wavelength Division Multiplexing) enables large-volume data transfer.

The principal three technological fields in the ICT (Information and Communication Technologies) are *computing*, *networking*, and *interfacing* technologies. In all three technological fields, the amount of information handled and the speed of information processing/transmission are reaching *peta-scale*. For instance, in large-scale numerical computations and large-scale simulations, the number of objects in computations/simulations and the amount of data generated from computations/simulations are reaching peta-scale. Similarly, the maximum communication speed of a single optical fiber reaches several tens of tera-bit/s, and the bandwidth-delay product of a wide-area optical network exceeds several peta-bits.

To realize peta-scale computing, networking, and interfacing technologies, individual research and development in each technological field should not suffice. Instead, a new ICT paradigm *peta-flow computing*, which enables peta-scale information processing and communication by synergetic integration of three technological fields, is desired. Although individual advancement and enhancement of computing, networking, and interfacing technologies have been progressing, framework for integrating those three technological fields is lacking.

In this paper, we first discuss short-, mid-, and long-term goals toward realization of peta-flow computing, which enables peta-scale information processing and communication. We then present a promising application for peta-flow computing, a large-scale upper airway flow simulation, and discuss its requirements. We also discuss challenges and implications of three technological fields of peta-flow computing — peta-scale computing, peta-scale networking, and peta-scale interfacing — on the large-scale upper airway flow simulation.

The organization of this paper is as follows. Section 2 summarizes related fields to peta-flow computing. In Section 3, we discuss short-, mid-, and long-term goals toward realization of peta-flow computing. Section 4 introduces the large-scale upper airway flow simulation as a promising application for peta-flow computing, followed by discussion on its open issues. Section 5 discuss challenges and implications of three technological fields of peta-flow computing — peta-scale computing, peta-scale networking, and peta-scale interfacing — on the large-scale upper airway flow simulation. Section 6 discusses necessity and importance of synergetic integration of three technological fields. Finally, Section 7 concludes this paper and presents our vision on peta-flow computing.

2 Related Fields

Grid computing is a concept of realizing scalable computing by virtually integrating geographically-dispersed computing resources. Through a wide-area network such as the Internet, Grid computing virtually integrates computing and storage resources, and provides computing service to end users.

Cloud computing is a similar concept with the Grid computing; it is an attempt to utilize computing and storage resources flexibly through the Internet. Cloud computing is a concept related to the usage of computing resources, and several types of service provisioning such as SaaS (Software as a Service), PaaS (Platform as a Service), and IaaS (Infrastructure as a Service) are considered.

Grid computing, Cloud computing, and related distributed computing technologies mainly focus on the improvement of computing and storage scalability in terms of data size. Although research and development of individual component technologies have been initiated regarding peta-scale networking and peta-scale interfacing, advancement and integration of computing, networking, and interfacing technologies are required.

3 Goals

Peta-flow computing integrates the principal three technological fields in the ICT (i.e., computing, networking, and interfacing technologies), and its goal is multi-dimensional.

The short-term goal of peta-flow computing is enhancing the conventional computing, networking, and interfacing technologies including Grid computing and Cloud computing in terms of the the amount of information handled and the speed of information processing/transmission. Computing, networking, and interfacing technologies have been already shifting from giga-scale to tera-scale. Thus, stable migration from giga-scale technologies to tera-scale technologies are strongly required.

The mid-term goal of peta-flow computing is establishment of fundamental technologies for peta-flow computing such as *networking-aware* computing, *interfacing-aware computing*, and *networking-aware* interfacing technologies by partial integration of peta-scale computing, networking, and interfacing technologies.

The long-term goal of peta-flow computing is ultimately creation of a new communication paradigm among human beings, which might be called *peta-scale communication*, based on peta-flow computing technologies. In other words, the ultimate goal of the peta-flow computing would be supporting human beings' various activities.

4 Example Application: Large-Scale Upper Airway Flow Simulation

The most promising applications for peta-flow computing exist in the filed of scientific research because of its complexity and high resource requirements.

One of the promising applications for peta-flow computing is a large-scale *upper airway flow simulation*. It is significantly important to reveal the sound generation mechanism of a sibilant /s/ systematically because the sibilant /s/ is pronounced in the most of languages and most critical phoneme distorted by dental therapies. Currently, it is possible to visualize the simulated oral air flow with improvement of the computational performance [7]. However, it is still challenging to simulate a sound propagation along with the oral air flow. This type of numerical simulations is called *Computational Aero-Acoustic (CAA)* simulation. In CAA, approximately one to ten billion (i.e., peta-scale) meshes in FEM (Finite Element Method) are required to regenerate the sound of the sibilant /s/ [5].

5 Enabling Technologies

In what follows, challenges and implications of three technological fields of peta-flow computing — peta-scale computing, peta-scale networking, and peta-scale interfacing — on the large-scale upper airway flow simulation are discussed.

5.1 Peta-scale computing

Peta-scale computing is a set of technologies for enabling large-scale computing for geographically-dispersed large-volume data. It should be noted that pure large-scale computing, which is independent of networking and interfacing technologies, is insufficient. Instead, integrated large-scale computing with networking and interfacing technologies is necessary.

In the large-scale upper airway flow simulation, its goal is to discover the principals of the sibilant and vowel generated by oral airflow in the realistic geometries of human oral shapes. The most significant issue of the simulation is the resolution of vortexes, which directly affects the sound signals. As the sibilant is broad-band noise ranging from 4,000 [Hz] to 16,000Hz, the space resolution of vortexes need to be as small as the sound sources can be calculated. Lighthill showed the far field sound propagation could be computed.

Currently, the prediction up to 4,000 [Hz] is achieved, but higher computation accuracy of eddies is needed for predicting over 4,000 [Hz] signals. For predicting higher frequency signals, quadruple elements must be inserted in the normal direction near the wall, which accounts for approximately 576,000,000 elements. The resulting data size reaches 18 [Tbyte] for 10,000 time step simulations. After performing CFD (Computational Fluid Dynamics) analysis, CAA (Computational Aero Acoustics) analysis is performed by importing 88 [Tbyte] of data.

Challenge here is that 18 [Tbyte] of data is converted to the frequency domain by the FFT (Fast Fourier Transform) and mapped to CAA mesh elements, and finally computed Hermhortz equation by FEM (Finite Element Method) to take the quadruple sound sources into consideration. For just a single case, the simulation requires 18 [Tbyte] plus CAA data size (approximately 1–10 [Gbyte]). If we have twelve cases, the total data size exceeds peta-byte.

5.2 Peta-scale networking

Peta-scale networking is a set of technologies for enabling transparent access to geographically-dispersed large-volume data. Again, it should be noted that pure high-speed networking, which is independent of computing and interfacing technologies, is insufficient. Instead, integrated high-speed networking with computing and interfacing technologies is necessary.

For instance, peta-scale and data-intensive networking technologies for realizing highly dependable and efficient large-volume data transfer in peta-flow computing are required.

Challenges for realizing large-volume data transfer in peta-flow computing are multi-dimensional: e.g., dependability, efficiency, generality, and easy deployment. Data transfer in peta-flow computing is data-intensive; i.e., a large amount of data have to be transferred among computing resources. The size of transferred data ranges from several kilo-bytes for control messages to several peta-bytes for simulation/experimentation results. Since peta-flow computing requires large-volume data and also large-volume computing resources, both of which must be well coordinated and integrated in several ways.

A network middleware should be one of promising solutions since it is desirable to handle and manage the large-volume data transfer at a middleware level. This is because the key for realizing large-volume data transfer in peta-flow computing is to develop computing-aware high-speed networking technologies. The network middleware for peta-flow computing can work as glue for connecting both networking and computing resources.

Fundamental networking technologies for large-volume data transfer in peta-flow computing should be developed. The multi-dimensional issues in peta-flow computing could be solved using several approaches such as mathematical modeling, simulation, and experiments.

5.3 Peta-scale interfacing

Peta-scale interfacing is a set of technologies for enabling input/output of geographically-dispersed large-volume data from/to users. Once again, it should be noted that pure large-scale interfacing, which is independent of computing and networking technologies, is insufficient. Instead, integrated large-scale interfacing with computing and networking technologies is necessary.

In a context of the large-scale upper airway flow simulation, conventional researchers have used surface-based visualization techniques to understand the large-scale FEM simulation results using sectional slice or boundary geometry [6]. Although the visualization result can provide useful information, it is limited to two-dimensional spaces. Before an adequate surface is determined, it is often necessary to grasp the spatial distribution of the related physical quantities. Although a volume rendering technique is desirable for such purposes, it is difficult for a conventional volume rendering technique to deal with a large-scale irregular volume dataset. This difficulty arises since it requires the entire volume dataset to be stored in a single computational node in order to calculate the visibility of the mesh cell at each viewpoint. It is apparent that such requirements are impractical, since the whole computational space is divided into multiple sub-volumes when a large scale simulation model is calculated using a distributed computational resource.

There is a strategy in which each sub-volume is rendered and the resulting sub-images are composited in the visibility order [1,2,4]. But, this strategy will fail when the shape of the sub-volume is concave (see Fig. 1). Thus, a sorting-

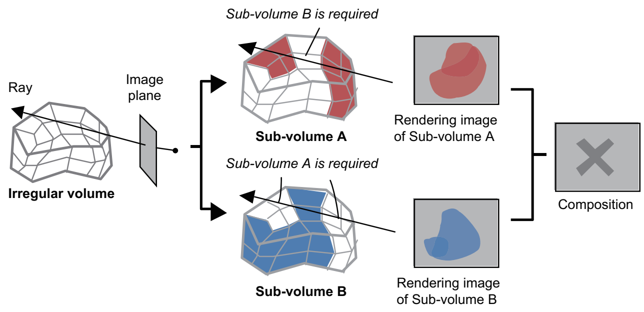

Figure 1: Large-scale irregular volume rendering in the distributed computing environment

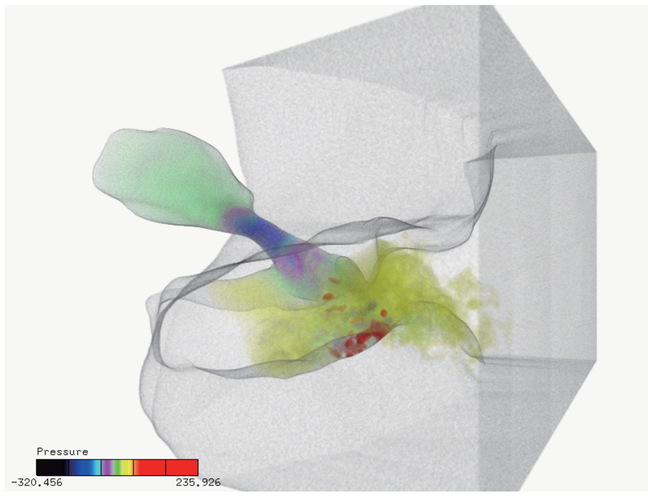

Figure 2: Rendering result of oral airflow simulation dataset (pressure value field)

free irregular volume rendering technique would be a good candidate for our purpose and would be well suited to cell-by-cell processing, which does not require entire cells to be stored in a single memory space [7] (see Fig. 2). A sorting-free technique for irregular volume rendering of a peta-scale irregular volume dataset generated from a distributed CFD calculation is thus required. The technique should be applied to CFD simulation results from modeling an oral airflow field to confirm its effectiveness.

6 Toward Synergetic Integration

One of the most important concept for advancing information and communication technologies is *simplification*, which splits a large complex problem into several small simple sub-problems. For instance, the divide and conquer method in the computer science field divides a large complex problem (e.g., a sorting problem of a large number of elements) into several small simple problems, each of which can be easily solved with computers. In the information networking field, the OSI reference model, which is an abstraction of complex networking protocol as a stack of independent protocol layers, has been widely accepted for simplifying design and implementations of network protocols.

Contrary to the concept of simplification for solving a large complex problem, there is an opposite view on complex systems — a complex systems naturally needs complexity. Namely, a certain level of unification and/or integration is necessary for realizing complex functions. For instance, a brain of human being is a very large-scale complex system with advanced functionalities. It has been well known that brain mechanisms for computation and remembrance are not separable. In other words, neurons in the brain perform multiple functions as computer, network, and storage. On the other hand, in the information networking field, a cross-layer approach for designing an advanced networking protocol, which actively integrates adjacent networking layers (e.g., data-link layer and network layer), has been attracting attention.

For realizing peta-flow computing, which enables peta-scale information processing and communication, a certain level of unification and/or integration of computing, networking, and interfacing technologies would be necessary. However, tactless integration of computing, networking, and interfacing technologies just complicates the problem, and make peta-flow computing difficult to realize. The key for realization of peta-flow computing is to develop a methodology for systematically unifying/integrating computing, networking, and interfacing technologies while maintaining their in dependency and maintaining the complexity.

7 Conclusion

High-performance computing such as large-scale computations/simulations have been leading applications of information and communication technologies, and this tendency is expected to continue even in the peta-scale era. For enabling peta-scale applications such as a large-scale upper airway flow simulation, establishment of fundamental technologies such as computing, networking, and interfacing technology has been strongly required. For systematically unifying/integrating computing, networking, and interfacing technologies, there still remain many open issues such as development of methodologies for designing and controlling large-scale complex systems.

Peta-flow computing will be built upon a wide spectrum of computing, networking, and interfacing technologies. Not just crossovers of computing, networking, and interfacing technologies, but also crossovers of interdisciplinary researchers in the filed of, for instance, computer science, physics, chemistry, biology, and medical science should be the key for accelerating realization of peta-scale computing.

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