Network Laboratory System for Space Simulations

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We developed a network laboratory system for space/astro simulations. It consists of online simulators and database contents. Web-based user interfaces were developed to enable users to input simulation parameters, carry out simulations in a remote server computer, and visualize the simulation results through computer network. For astrophysical magnetohydrodynamic (MHD) simulations, we developed a coordinated astronomical numerical softwares (CANS), which contains simulation engines and various sample packages of astrophysical simulations. In each package, modules which set up initial conditions, boundary conditions, simulation parameters, and documentations are included. CANS is designed such that users can learn MHD simulations through examples. Users can apply CANS to their own problem by slightly modifying the example most close to their problem. The network laboratory system is useful for both frontier research and education/popularization of space/astro simulations.

1. Introduction

As a project of Japan Science and Technology Corporation (ACT-JST), we developed a network laboratory system for space/astro simulations. The purpose of this project was to develop a virtual laboratory of space/astro simulations by using high speed computer networks. Figure 1 schematically shows the concept of this numerical laboratory. The team members of this project is shown in Table 1.

Fig. 1. A schematic picture of the network laboratory system for space/astro simulations.

The network laboratory system consists of web-based simulators and database contents (figure 2). The web-based simulator enables users to carry out simulations and visualize the simulation results remotely by specifying simulation parameters using a web-browser. Web interfaces enable users to access database contents such as code libraries, images/movies of simulation results, and documents.

2. Web Pages of the Network Laboratory System

Figure 3 shows the homepage of the network laboratory system. The URL of this page is http://www.astro.phys.s.chiba-u.ac.jp/netlab/

We have two main contents. One is the space plasma simulator and the other is the astro-simulator. The space plasma simulator includes simulator sites and database sites. The simulator site includes web-pages such as full particle...
simulations, hybrid simulations, MHD simulations, plasma wave linear analysis, and nonlinear time series analysis. The database site contains web pages on solar terrestrial phenomena and virtual exhibition of space science (VESS).

In the following, we introduce the main content of the astro-simulator called CANS (coordinated astronomical numerical software).

3. Coordinated Astronomical Numerical Software (CANS)

We have developed an integrated software CANS for astrophysical MHD simulations. CANS is designed such that (1) users can learn astrophysical MHD simulations through examples, and (2) they can carry out new simulations easily by combining ready-made modules. The basic idea behind this is that even when the source code is available, it is hard for users to carry out simulations. Good examples are very helpful for users.

Figure 4 schematically shows the design of CANS. CANS consists of program modules and packages of basic simulation exercises. Program modules include simulation engines and modules to incorporate various physical processes.

3.1 Basic Equations

CANS solves the following time-dependent nonlinear MHD equations.

\[
\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{v}) = 0
\]

\[
\frac{\partial \mathbf{v}}{\partial t} + \rho (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla P + \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi} + \rho g
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B} - \eta \nabla \times \mathbf{B})
\]

\[
\frac{\partial \rho \epsilon}{\partial t} + \nabla (\rho \epsilon \mathbf{v}) + P \nabla \mathbf{v} = Q^+ - Q_{rad}
\]

Here \(g\) is gravity, \(\eta\) is resistivity, \(Q^+\) is the heating term including Joule heating, and \(Q_{rad}\) is the radiative cooling. We can also include anisotropic heat conduction depending on the direction of magnetic fields.

3.2 Simulation Engines

The MHD equations are solved by finite difference methods. We call these solvers as simulation engines. 1D, 2D and 3D engines in Cartesian, cylindrical, and spherical coordinates are installed. In addition to the classical engine based on the modified Lax-Wendroff method with artificial viscosity, we installed modern engines based on the CIP-MOCCT method (Kudoh et al. 1999) and the Roe scheme. The CIP-MOCCT scheme adopts the CIP method (Yabe 1991) in hydrodynamical part and MOCCT (Method Of Characteristics + Constrained Transport) scheme (Stone et al. 1992) to solve the induction equation and to evaluate the Lorentz force. The Roe scheme evaluates the flux across the mesh boundary by using the approximate Riemann solver (e.g., Brio and Wu 1988). The simulation engines are pluggable to the platform of the simulator. Thus, users can change simulation engines according to the problem.

The simulation engines are highly vectorized. They have been parallelized by using MPI. The parallel performance when using \(1500 \times 1000 \times 500\) mesh points is more than 99.9%.

3.3 Packages of Basic Simulation Exercises

Table 2 shows packages of basic simulation exercises. Each package includes modules to set up the mesh points, initial conditions, boundary conditions, parameter inputs, visualization programs written in IDL, and documents on model setup and input parameters.

Figure 5 shows snapshots of simulation results by CANS2D. Figure 6 shows the result of 3D MHD simulation of buoyant rise of twisted magnetic flux tube in the solar atmosphere carried out by CANS3D.

3.4 Web Pages of Basic Simulation Exercises

Figure 7 shows the Web page of CANS1D. Users can choose a problem from the menu (left) and can browse its contents (right). The explanation page includes the description of the problem, basic equations, model setup and simulation results. Users can also download the documents in PDF format. Figure 8 shows the movie page. The user interface of the movie player is written in Javascript.

Users can also analyze the simulation results and visualize them by using a web browser. We adopted a commercial
Table 2. CANS modules for basic exercises of astrophysical fluid/MHD simulations.

- **md_advect**: advection
- **md_awdecay**: decay of large amplitude Alfven Wave
- **md_cloud**: collapse of self-gravitating cloud
- **md_cme**: Solar coronal mass ejection
- **md_corjet**: heat conduction
- **md_cwdecay**: decay of large amplitude Alfven Wave
- **md_cme**: Solar coronal mass ejection
- **md_cndtb**: heat conduction
- **md_corjet**: solar coronal jet
- **md_cme**: emergence of solar magnetic flux
- **md_cwdecay**: Kelvin Helmholtz instability
- **md_mhdsedov**: MHD supernova remnant
- **md_mhdshktb**: MHD shocktube
- **md_mhdsedov**: propagation of linear MHD wave
- **md_mhdshktb**: magneto-rotational instability
- **md_reccnd**: reconnection heat conduction
- **md_recon**: magnetic reconnection
- **md_reccnd**: Rayleigh Taylor instability
- **md_shkref**: Sedov solution
- **md_shkref**: shock reflection (fluid)
- **md_shktb**: shock tube (fluid)
- **md_thinst**: thermal instability

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3.5 Online Simulator and Network Visualization System

We developed NetCANS by which users can carry out simulations and visualize the simulation results through internet by using the web browser. NetCANS is an interface to the commercial software MAST. MAST has an adopter to the 3D visualization software AVS. It also supports parameter inputs on the web browser. Figure 10 shows the web-pages of NetCANS. By using a web-browser, users can choose a problem, input simulation parameters, carry out simulations by using the remote server computer, and visualize the simulation results.
4. Application to Frontier Research

CANS has been applied to various problems in astrophysics. Asai et al. (2004) applied CANS to simulate the effects of magnetic fields and heat conduction on the evolution of moving subclumps in cluster of galaxies. Figure 11 shows the results obtained by using CANS3D with heat conduction module. Recent observations by Chandra X-ray satellite revealed the existence of sharp temperature discontinuity at the front of a moving subclump in cluster of galaxies. The discontinuity is called the cold front. Since the heat conductivity is high in high temperature plasma, such fronts cannot be maintained unless heat conduction is suppressed. The top panel of figure 11 shows the distribution of temperature when initially uniform vertical magnetic fields exist. The bottom panel of figure 11 shows the result when magnetic field does not exist. Heat conduction smears the temperature gradient unless magnetic fields suppress the heat conduction across the front.

5. Simulation Summer School

The network laboratory system has been used as an educational tool to introduce space/astro simulations to graduate students and young scientists. In September 2001, we held a summer school of fluid/MHD simulations in astrophysics at Chiba University. In 2002, we had a summer school on numerical simulations in space and astrophysical plasmas at Nagoya University. In this summer school, we had fluid/MHD simulation course and particle/hybrid simulation course. More than 100 graduate students/young scientists from all over Japan attended the summer school. In the summer school, after lectures on basics of numerical simulations, attendants are organized into sub-groups according to the problems they choose. They carried out numerical simulations by modifying the original code. On the last day, each group gave presentation of their simulation results. In 2003 and 2004, we held the simulation summer school at Chiba University.

6. Summary

We have developed a network laboratory system for space and astrophysical simulations. The network laboratory system has been proven to be useful not only for researchers but for beginners of numerical simulations.

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References