Development of PIV Web Laboratory and Its Application

● Taiyo Maeda ● Naoki Onishi ● Yoshimasa Kadooka ● Yoshio Tago

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Particle image velocimetry (PIV) is an experimental method of researching fluids that is employed in fields such as automobiles, aviation, civil engineering, and medicine. It is used as a complement to computer simulation. Three-dimensional analysis of PIV data requires a high-performance computer, large-capacity storage, and a powerful visualization engine. Also, researchers require an environment for collaborative PIV research using powerful computer resources. The PIV Web Laboratory (PIV-WL) was developed to meet this requirement. This system is based on UNICORE Grid middleware and has multi-job management and 3D remote visualization functions. We used this system to analyze the flow fields on delta wings and created a collaborative research environment in which many users can manipulate visualization results simultaneously by remote control.

1. Introduction

Recently, Information Technologies (ITs) have been contributing to the research of flow-field analysis. Two examples of these technologies are flow-field analysis using computer simulations and image analysis for measuring velocity vectors and other physical quantities on experimental flow-field systems based on particle image velocimetry (PIV).

In PIV, small particles traveling in a liquid medium are illuminated by a thin sheet of laser light and the illuminated particles are photographed using a CCD camera. The images are then used to calculate the velocity vectors of the flow field. **Figure 1** shows the basic equipment for PIV experiments. KMU-PIV is a PIV analysis software developed by Korea Maritime University (KMU). The advantages of PIV compared with conventional methods are that it enables many points on a flow field to be measured simultaneously and the measurements are easier to make. Because of these advantages, PIV is used as the standard method in most areas of flow-field analysis. For example, PIV is used to analyze airflow around airplane wings, fuel flow in car engines, and blood flow in the human body.

The Computational Grid technique$^{1)}$ is used for remotely visualizing data from PIV, which is a state-of-the-art quantitative flow velocity measurement technique.$^{2)}$ The Computational Grid has four layers: the infrastructure, common services, programming tools/problem solving environment (PSE), and applications. We have developed a PSE system called the PIV Web Visualization (PIV-WV) system using the Grid common service tool Globus (http://www.globus.org), the Java programming language, and a computer system we call the Grid Portal that allows us to view the visualization resources on networks as a unified whole.$^{3)}$

Although PIV experiments are evolving from 2D to 3D measurement, this PIV-WV system is based on 2D PIV experiments. With the increase in the number of PIV applications and the rapid

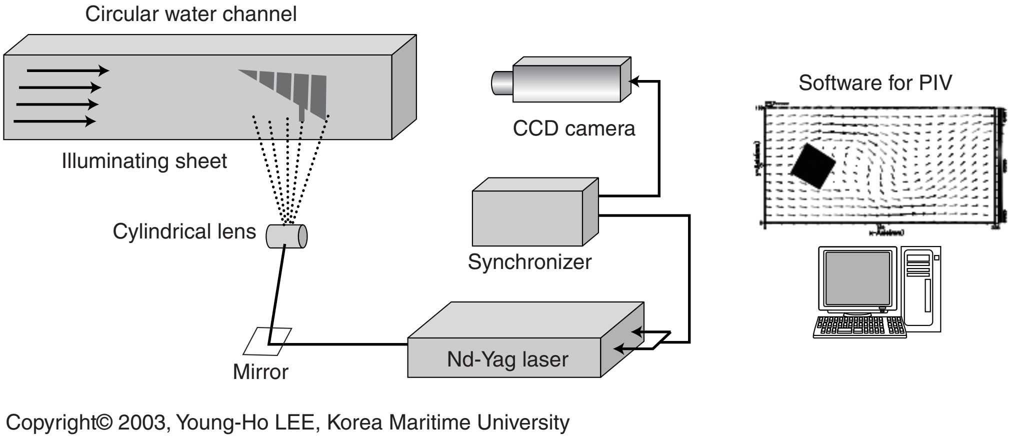


Figure 1
Experimental equipment for PIV.

changes in PIV techniques, scientists and engineers are anticipating the appearance of an environment that will enable powerful, collaborative PIV research. However, to realize such an environment, it will be necessary to quickly calculate many velocity vectors distributed in 3D space and display the results of flow-field analysis by visualizing images of physical quantities, which will require high-speed computers, large-capacity storage devices, and other powerful computer resources.

To satisfy these requirements, we have extended the PIV-WV system to establish a PIV collaborative research environment called the PIV Web laboratory (PIV-WL) using remote visualization under a multi-user environment and Grid technology.[4),5)] The PIV-WL consists of a portal server, three engines (broker engine, calculation engine, and multi-visualization engine), and a database system. The portal server enables users to input instructions to use the resources of PIV-WL according to the user's requests. All data related to users' PIV experiments are stored in a database system, and the search engine allows users to search for data in the database system.

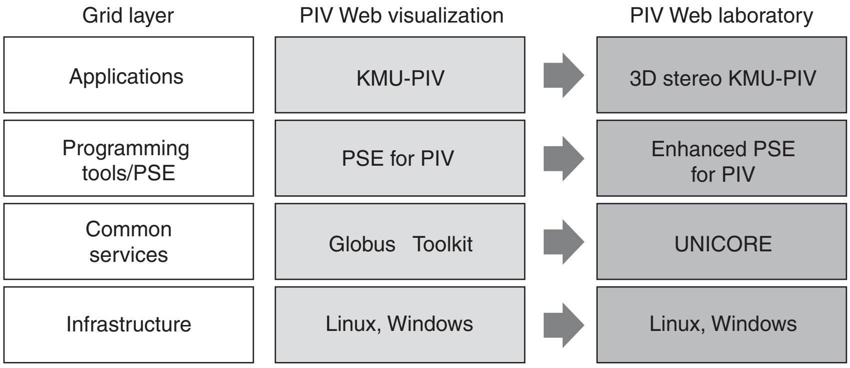
The purpose of this paper is to show that PIV-WL is useful for analyzing and visualizing 3D PIV experiments for a delta wing.

2. From PIV Web visualization to PIV Grid visualization

The PIV-WV was developed on the Internet by Kanazawa University (KU) and KMU and then tested.[6)] It includes three subsystems: a PIV analysis engine, an animation server, and a PIV portal. The PIV analysis engine makes it possible to calculate velocity vectors and many types of physical quantities based on raw data obtained from PIV experimental systems. The animation server makes it possible to visualize the data obtained from the PIV analysis engine. The PIV portal makes it easy for users to access the PIV analysis engine and animation server without needing to be aware of the system configuration.

The PIV analysis engine is located on the KMU campus, and the other subsystems are at KU. These subsystems are connected by using Grid technology, so any user can use the PIV-WV system just by accessing the PIV portal site.

Our target for this research is to realize a collaborative, Grid-based research environment for fluid mechanics on the Internet. We developed PIV-WV according to the Grid Layer as shown in **Figure 2**. The infrastructure is based on Linux and Windows, Globus Toolkit is used for the common services layer, and the application layer is KMU-PIV. We have developed a new PSE as a programming tool.



Grid layer	PIV Web visualization		PIV Web laboratory
Applications	KMU-PIV	➡	3D stereo KMU-PIV
Programming tools/PSE	PSE for PIV	➡	Enhanced PSE for PIV
Common services	Globus Toolkit	➡	UNICORE
Infrastructure	Linux, Windows	➡	Linux, Windows

Figure 2
New technologies introduced in PIV-WL.

We met some obstacles when we extended PIV-WV to PIV-WL. The first one was that we could not manage the status of the Windows machine that runs the KMU-PIV engine. More specifically, although we can manipulate the KMU-PIV engine on a Windows platform by connecting with the Grid environment through a bridge and wrapper we developed, we cannot check the status of the job being executed. As a result, users do not know whether their jobs have been completed. The second obstacle is about security. The computer resources of a PIV-WL are not always within the same campus and behind the same firewall. Moreover, the communication between different PIV-WLs should be done through a firewall. However, Globus Toolkit needs some open TCP ports, so a firewall will be of no service. To solve these two problems, we used UNICORE (http://www.unicore.de/) as the common services layer of the Grid instead of Globus Toolkit. UNICORE was developed as a Grid platform for UNIX/Linux, but we have succeeded in making it work on Windows.

We have introduced new technologies to enhance PSE for PIV, for example, parallel computing to calculate many velocity vectors and physical quantities, an advanced 3D visualization and volume modeling visualization engine called Amira,7) and a VNC (Virtual Network Computing) server,8) which is software that makes it possible to view results and fully interact with a remote computer and a database system. To adequately manage these functions, we have also developed a portal server and broker. Moreover, the KMU-PIV has been enhanced so it is capable of stereoscopic 3D PIV.

3. PIV Web Laboratory

We have introduced the concept of PIV-WL in order to meet three requirements. The first is to provide sufficient computational power to calculate many velocity vectors and many kinds of physical quantities generated in a PIV experimental system. For a 3D PIV experiment, the required computational power depends on the volume of data obtained by the PIV experimental system and PIV researchers would like to have access to all the resources they need whenever they are needed. The second requirement is to provide a high-performance visualization engine. It is indispensable for PIV researchers to have such an engine to show the results of PIV analysis, especially for a 3D system. The third requirement is to provide researchers with a collaborative workbench. For flow-fluid research to evolve using PIV experimental systems, it is very important to store the results obtained by PIV researchers and make them available to anybody who wishes to show them. To realize such a PIV-WL system, we have introduced the architecture shown in **Figure 3**.

The first requirement—providing sufficient

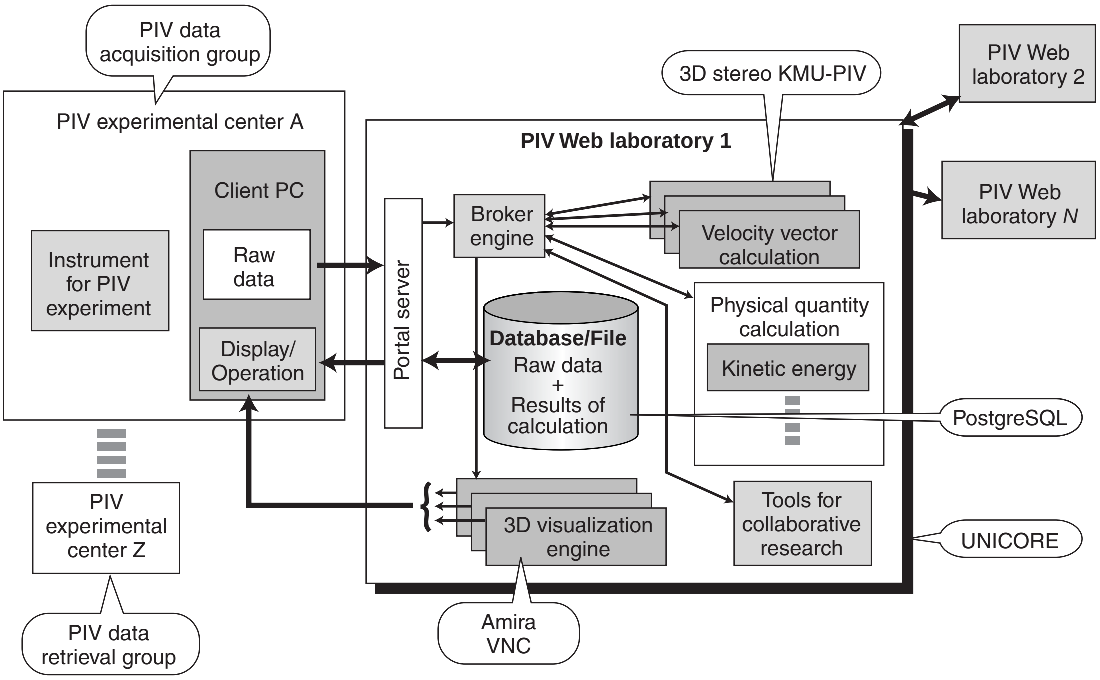


Figure 3
Architecture of PIV-WL.

computational power—can be met by introducing parallel computing techniques. In PIV-WV, the calculations done to obtain velocity vectors and physical quantities have been executed sequentially, so users often have to wait a very long time for their calculations to finish. However, by using parallel computing, users can get their results almost immediately.

For the second requirement—providing a high-performance visualization engine—we introduced an advanced 3D visualization and volume modeling visualization engine called Amira (http://www.amiravis.com/). Amira makes it possible to visualize the results of calculations as 3D data so complex flow fields can be understood visually. The user can manipulate the 3D images freely on a browser over the Internet. To realize this remote visualization function, the 3D visualization engine uses a VNC server.[8]

For the third requirement—providing a collaborative workbench—we introduced a database system in PIV-WL to make it easy to find the results of PIV experiments reported by any researcher. The data obtained by the calculation engines are stored in a database based on postgreSQL server in a format that enables Amira to effectively visualize it. In this architecture, many engines need to be managed as shown in Figure 3. To achieve this, we developed a broker engine to realize easy operation without the need to know about the individual engines. The broker engine assigns the most suitable engine to be used in each step.

There are two groups of users in PIV-WL. The first is the PIV data acquisition group, which directly accesses CCD images (flow fields in 2D and 3D). This group can calculate velocity vectors at very high speed using a high-throughput computing Grid. The velocity vector is stored in a database, together with other physical quantities such as kinetic energy and vorticity. Each member of this group can access the visualization engine at the same time and can visualize their physical quantities. The second group is the PIV data retrieval group. This group accesses the database, searches for a physical quantity, and then visualizes it. Multiple users can visualize various physical quantities on the visualization engine at the same time. Moreover, 3D animations of physical quantities can be visualized and manipulated on the users' displays. Figure 3 shows the relation between the PIV experiment centers and PIV-WLs.

PIV-WL can be widely distributed geographically, and other PIV-WLs will be constructed using engines other than KMU-PIV that will have their own unique features. These laboratories will be interconnected using Grid technology, consequently researchers will be able to access any other PIV-WL whenever they wish, use a PIV-WL's computer resources, and retrieve its data.

We will now describe the main functions of PIV-WL. The first main function calculates velocity vectors and physical quantities. The raw data generated in a PIV experimental system at the user side is input to the PIV calculation engines through a portal server. The engines then calculate the velocity vectors and physical quantities and forward them to the database/file system. The second main function stores and retrieves the results of PIV experiments. The calculation results are stored in the database/file system together with the raw data, PIV experiment conditions, and other data. This data is retrieved and processed according to the user's instructions from the portal server. The data in this database is very useful for collaborative research of flow fields. The third main function is for remote multi-visualization. The results created on a PIV calculation engine are sent to the animation server through the Grid portal as requested by the client. PIV animation is generated on the animation server using the Amira advanced 3D visualization and volume modeling visualization engine and can then be freely displayed and manipulated by many users simultaneously on a Web browser.

4. Results and discussions

4.1 Experimental conditions at the user side

We adopted this PIV-WL system to analyze the vortices generated on a delta wing. The equipment for the 3D PIV experiment was located at KMU, which accessed the PIV-WL system as a member of a PIV data acquisition group.

Two types of delta wing with the dimensions shown in **Figure 4** were fixed in a tank. One of the delta wings had a Leading Edge Extension (LEX) to exhaust the generation of vortexes, and the other was a simple triangle with no LEX. Each wing was mounted on the angle controller shown

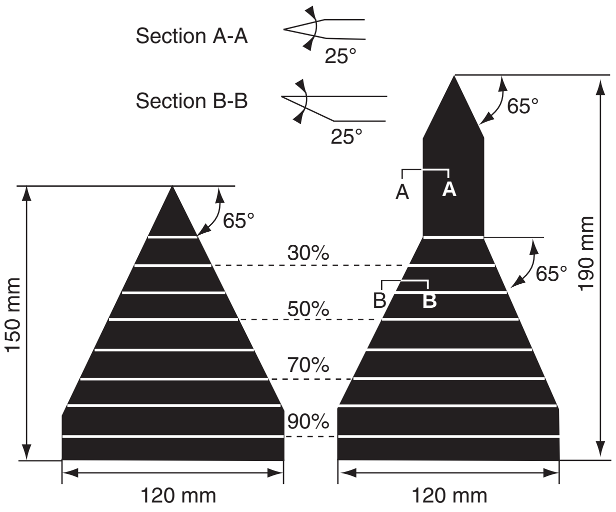


Figure 4
Dimensions of delta wings.

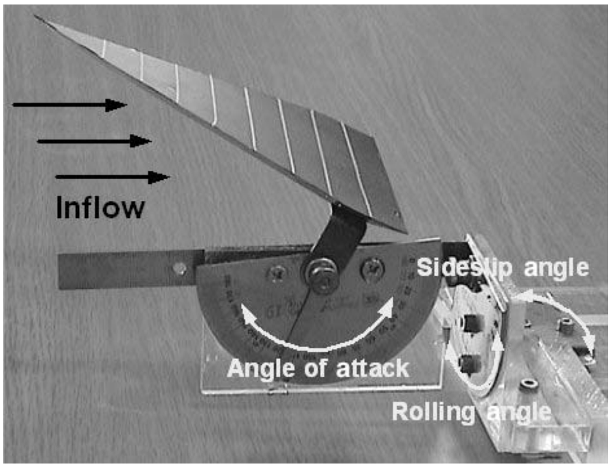


Figure 5
Angle controller.

in **Figure 5**. The angle of attack was set to 25 degrees, and the illuminated slice was on the 50% line.

Other conditions in this experiment are shown in **Table 1**.

As a result of this experiment, KMU obtained raw data for 3D PIV analysis of the delta wings. **Figure 6** shows raw CCD-camera data from the LEX delta wing. KMU submitted this data and the PIV experimental conditions shown in Table 1 by accessing the portal server of PIV-WL, the start page of which is shown in **Figure 7**.

4.2 Results of visualization

Based on the data submitted by the user, the PIV-WL system first calculated the velocity vectors of the delta wing. The results of this calculation were then sent to the 3D visualization engine and visualized by Amira. **Figure 8** shows the symmetrical development of the LEX vortex as it emerged into the delta wing vortex at an angle of attack (AOA) of 25 degrees. This phe-

Table 1
PIV experimental conditions.

Conditions	Item	Specification
Measuring condition	Working fluid	Water
	Temperature	20°C
	Particle	PVC (Poly Vinyl Chloride) 110 µm
Image processing	Recording time for high-speed camera	2 s
	Frame number for time-averaging	200 frames
	Identification	Cross correlation PIV
	Software	KMU-PIV
	Ratio of error vector	Less than 1%/frame
Identification condition	Maximum displacement	9 pixels
	Sampling rate	500 Hz

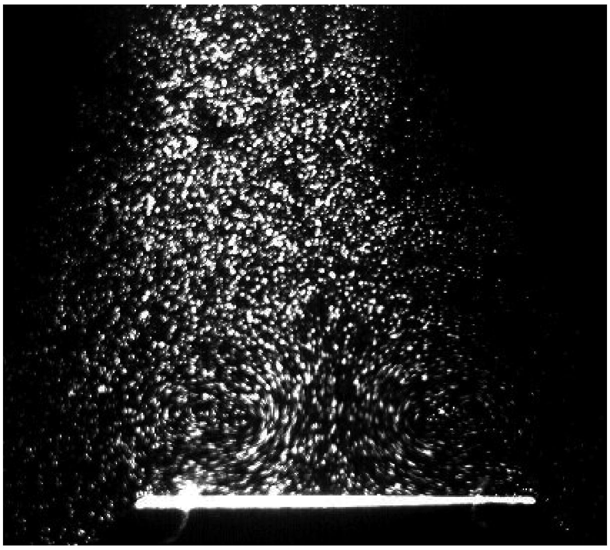


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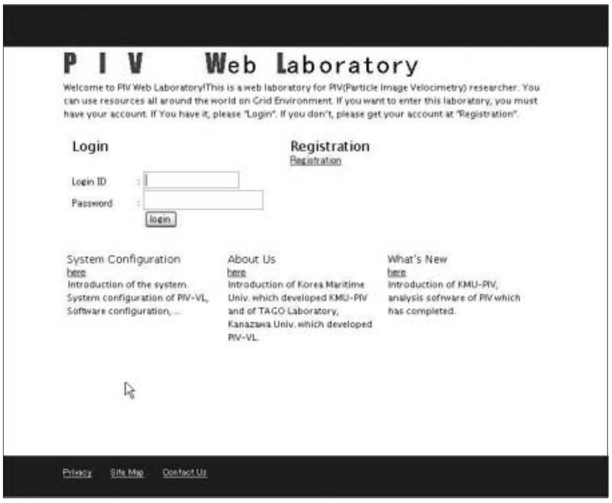
Figure 6
Example of raw data.



Welcome to PIV Web Laboratory!This is a web laboratory for PIV(Particle Image Velocimetry) researcher. You can use resources all around the world on Grid Environment. If you want to enter this laboratory, you must have your account. If You have it, please "Login". If you don't, please get your account at "Registration".

Introduction of the system. System configuration of PIV-VL, Software configuration, ...

Introduction of Korea Maritime Univ. which developed KMU-PIV and of TAGO Laboratory, Kanazawa Univ. which developed PIV-VL.

Introduction of KMU-PIV, analysis sofrware of PIV which has completed.

Figure 7
Start page of PIV-WL.

nomenon is typical in a LEX delta wing and is the basic mechanism of the augmented lift necessary for good operation of modern fighter aircraft. By using the PIV-WL system, the users can remotely see the image shown in Figure 8 and an animation that includes this figure on their browsers.

Figure 9 shows the directional structure in the cutting surface of the 3D vector field as visualized using the Line Integral Convolution (LIC) function of Amira.

The physical quantities that can be calculated based on the calculated velocity vectors include the kinetic energy, vorticity, velocity fluctuation, turbulence intensity, turbulence kinetic energy, and Reynolds stress. **Figure 10** shows four of these quantities as visualized by Amira for the LEX delta wing. Figure 10 (a) shows the kinetic energy distribution, including the Y (streamwise) component. Figure 10 (b) shows that each side has two symmetrical vortices with the same direction of rotation. The two vortices on the left, for example, are approaching each other, and, because they have the same clockwise rotation (indicated by the blue and white coloring), their vortices are strengthened. Figure 10 (c) shows the turbulence intensity of three fluctuating velocity components. As the figure shows, the intensity peaks are randomly distributed. Figure 10 (d) shows the distribution of Reynolds stress in the X (horizontal) and Y (streamwise) direction. Because the left and right vortexes rotate in opposite directions, the colored pattern shows the minus (-) and plus (+) contrast. The users can see images and animations of different physical quantities at the same time on their browsers.

We compared the turbulence kinetic energies of the two types of delta wings and found that the LEX had an even greater effect than we expected (**Figure 11**).

These results clearly show the efficiency of the LEX and also demonstrate Amira's ability to display different physical quantities and velocity vectors on the same image.

Multiple users in geographically distributed locations can see and manipulate the same visualized images and animations in the PIV-WL simultaneously by using the R2TIP (Remote Real Time Image Processing) system provided in the 3D visualization engine. We used the R2TIP system to access the animation server of KU from Texas A&M University (TAMU). We could then freely operate the animation server and see the results of visualizing PIV experimental data stored in the PIV-WL by the KMU.

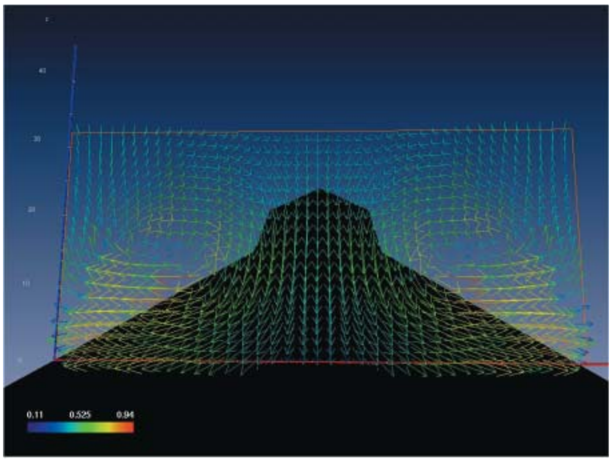


Figure 8
Velocity vectors on delta wing with LEX.

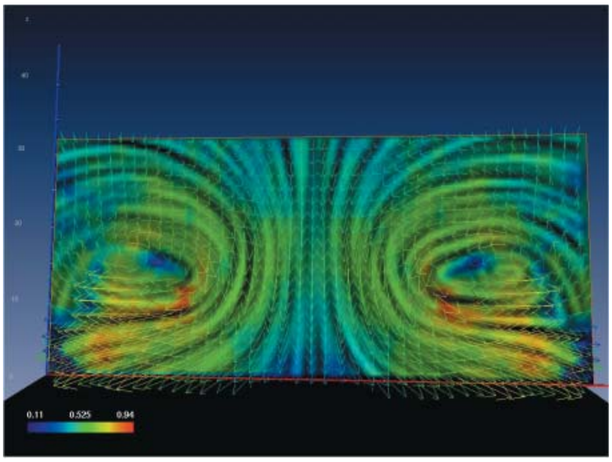
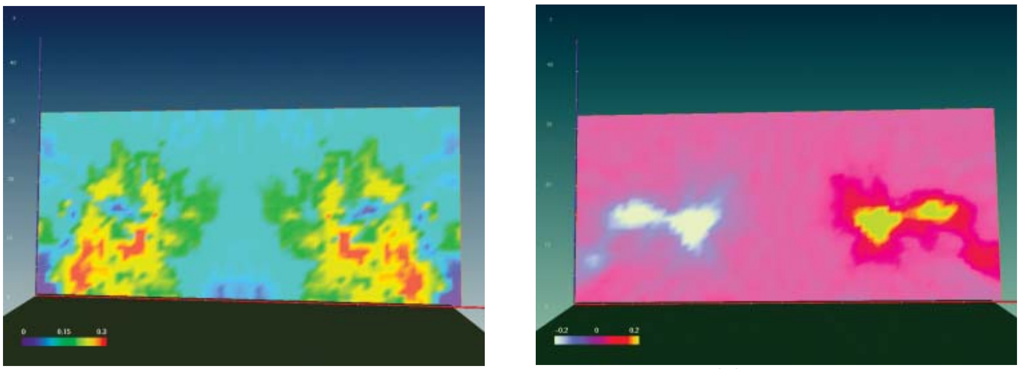
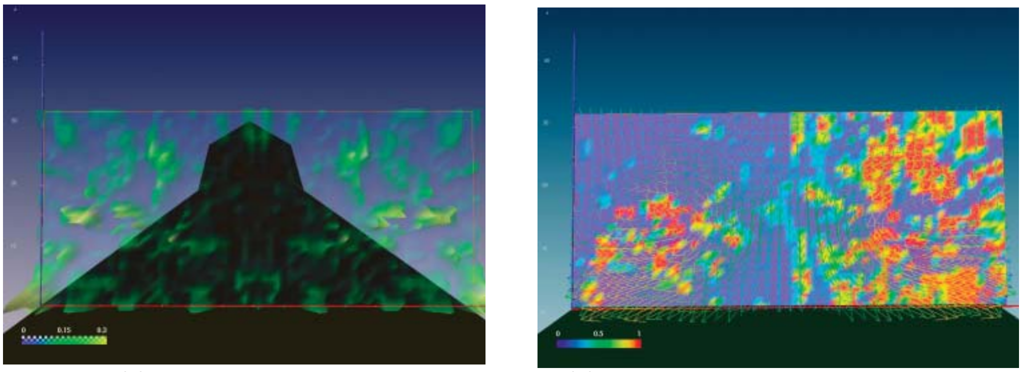


Figure 9
Velocity vectors visualized by LIC function of Amira.



(a) Kinetic energy (b) Vorticity



(c) Turbulence intensity (d) Reynolds stress in X and Y direction

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Figure 10
Visualization of physical quantities.

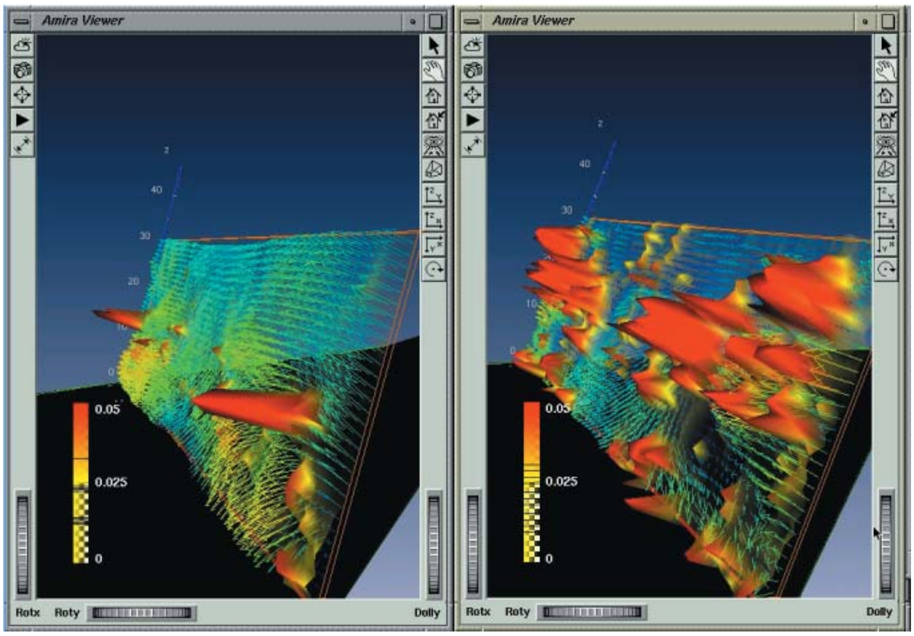

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Figure 11
Turbulence kinetic energies with LEX (left) and without LEX (right).

5. Conclusions

We developed the PIV-WL system by using Grid common services tool UNICORE, the Java programming language, and server systems. The system is composed of the 3D stereo KMU-PIV engine and a Grid portal, broker, database, Amira-based animation servers, and client PCs. We used this system for the practical flow-field analysis of delta wings. As a result, we developed a virtual environment for collaborative research using PIV experiments.

The system's powerful resources are easy to use and do not require any awareness of the individual computer resources that are being used to execute a job. The results obtained by the system are visualized by the animation server and can be seen simultaneously by multiple researchers in geographically dispersed locations. The system can therefore strongly assist in collaborative research.

The demands for more powerful computer resources, larger capacity storage devices, and higher performance visualization engines in PIV research will become large in the near future. We believe our PIV-WL system will help meet these demands.

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