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NETWORKED PSEUDO-DYNAMIC TESTING PART II : APPLICATION PROTOCOL APPROACH

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SUMMARY

Recently National Center for Research on Earthquake Engineering (NCREE), through the use of the Internet, has developed the platform entitled Internet-based Simulation for Earthquake Engineering (ISEE). This platform not only allows researchers around the world to visualize and take part in discussions of undergoing experiments synchronously, but also allows more than one laboratory to jointly carry out a single experiment. A computer platform, "Platform for Networked Structural Experiments (PNSE)," constructed based on Transmission Control Protocol / Internet Protocol (TCP/IP) is one of the two approaches under ISEE project. PNSE is a multi-client system composed of a command generation program and a number of facility control programs connected with a server program via TCP on the Internet. An application protocol named "Networked Structural Experiment Protocol (NSEP)" was proposed for PNSE. Domestic and transnational Pseudo-dynamic (PSD) tests were performed to verify the validity and efficiency of PNSE. Test results show that on PNSE, signals were correctly transmitted, significant laboratory events were promptly reflected, and the efficiency of data transmission was satisfactory.

INTRODUCTION

For structural laboratories to meet the increasing demands on testing large and realistic specimens, a more practical solution is to link a number of laboratories by the Internet to collaboratively perform a single experiment rather than endlessly increasing the capacity of structure laboratories. Researchers in Japan and Korea have conducted some tests jointly to investigate the practicability of pseudo dynamic tests between these two countries (Sugiura [1], Yun [2], and Watanabe [3]). The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program, envisioned by the National Science Foundation in USA, also aims at exploring the tremendous benefits of sharing and integrating laboratory resources via network (NEES [4], Mahin [5], and Kesselman [6]). Currently, a 3-D full-scale earthquake testing facility named E-Defense is under construction in Japan, meanwhile, an E-Defense Network (ED-Net) is also being constructed, which will provide tele-observation and tele-discussion capability to research institutes,

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universities, and private sectors in the near future (Ohtani [7]). A project, the Internet-based Simulation for Earthquake Engineering (ISEE), have been launched in National Center for Research on Earthquake Engineering (NCREE) in Taiwan to construct a platform that links numerical simulation programs and facility control programs around the world by the Internet for networked structural experiments (Tsai [8]).

This idea actually leads to a concept of a virtual laboratory which turns all those linked laboratories to be integrated parts of it. The benefits that can be obtained from such integration include saving unnecessary investment on testing facilities, exchanging experiences and technologies between laboratories, and sharing experimental data that leads to collaboration on research works between researchers. Within the framework of ISEE project, two approaches, the Database Approach (Yang [9]) and the Application Protocol Approach, provide different platforms to achieve this goal. A computer platform, "Platform for Networked Structural Experiments (PNSE)," was constructed based on the application protocol named "Networked Structural Experiment Protocol (NSEP)" in this study. The Buckling Restrained Braced (BRB) frame was tested to investigate and evaluate the preliminary feasibility of the proposed PNSE. A series of transnational Pseudo-dynamic (PSD) tests on a specimen composed of two Double-Skinned Concrete Filled Tubular (DSCFT) columns located in two different laboratories were conducted to verify the validity and efficiency of PNSE. The characteristic of environment independency of PNSE was also verified by a series of networked PSD tests on a full-scale 3-story 3-bay Concrete Filled steel Tube (CFT) and BRB composite frame. This paper briefly describes the architectures and practical implementation of the Application Protocol Approach.

The Transmission Control Protocol / Internet Protocol (TCP/IP) suite was designed as an open standard to meet the demand of data transmission on rigorous network conditions (Postel [10] and [11]). TCP guarantees reliable data transmission by providing services such as acknowledged delivery, error detection, retransmission if necessary, data sequence preservation, and flow control. IP provides addressing, routing, fragmentation and reassembly for data packets. TCP/IP stack thus handles all those tedious works for data transport between hosts on heterogeneous networks.

ARCHITECTURE OF PNSE

Overview

The architecture of PNSE is illustrated in Fig. 1. PNSE stress the successful progression of networked experiments rather than the functions of digital and video data storage and display on the Internet, which can be achieved by available commercial software such as Microsoft SQL server or Windows Media Player. Three types of modules on PNSE, the PNSE server, Command Generation Module (CGM), and Facility Control Modules (FCM) are connected by employing socket operations to utilize the TCP/IP suite to ensure high interoperability between heterogeneous network and working environments. PNSE is implemented by using the TCP connection for its simplicity and reliability. The TCP connection provides a connection-oriented services since a virtual circuit is established between two hosts and the connection exists until any side of a connection terminates it. The TCP connection does not reserve the data packet boundary but provides reliable data transport by automatically acknowledging data receipt, retransmitting data if an acknowledgment is not received, preserving data sequence, and avoiding duplication of data.

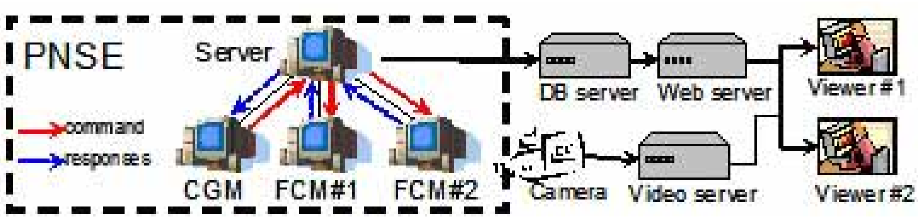


Fig. 1 Architecture of PNSE

PNSE is a multi-client system with two kinds of clients, the CGM and the FCMs, connecting to the server with a TCP connection. The PNSE server is essentially the core of the system and it plays a transfer post dispatching information to all clients. For any client, all messages and data must be sent to and received from the server. The reason that clients do not connect directly to each other is to simplify the network topology and hence the communication flow. This star topology makes each client communicate with the server only, instead of the many other clients. This may introduce more time needed to transfer data since all data must be sent to and then dispatched by the server. However, this design can largely reduces the complexity of the communication flow and hence saves the efforts needed for program development. Communication between the server and client is full-duplex transmission which means that either side of a connection can actively send and passively receive information to and from the other side at exactly the same time and thus to realize the goal of an event reflective platform.

The PNSE server

The PNSE server is essentially the information center of the platform. It provides services of message dispatch and data delivery for clients. Conceptually it is the center of the network topology, but here it is not the “processing center” which determines and controls the sequence of the work. The server also takes the responsibility of data storage and manages a simple login process for any connection attempt for security concern.

The CGM

The CGM calculates or prepares the commands to be imposed on the specimen. The module that generates commands can be a numerical integration algorithm in pseudo dynamic testing, a input module that queues predefined command profile in quasi-static testing, or simply an remote control application with an user interface that allows its user to enter commands dynamically. The CGM prepares commands for all FCMs and integrates them into a single packet (composite command) to send to the server for parsing and dispatching. It then waits for a data packet (critical response) sent by all FCMs and dispatched by the server as an indication of the completion of the command execution.

The FCM

The FCM receives the parsed commands from the PNSE server and controls the actuators to impose the commands on the specimen, then measures or calculates the critical responses and send them back to the server as a notification of the completion of command execution. When all FCMs complete execution of their own commands, the server notifies the CGM of this event and the CGM can then send the commands for the next step. The FCM on PNSE is quite the same as the traditional facility control program in a structural laboratory. It still controls the actuator motion, performs the data acquisition, alters the test running state if necessary, and displays the real time test results to its operator. One difference is that the FCM on PNSE executes the commands received from the PNSE server, instead of the commands generated by FCM. Another difference is that it is obligated to send the notification to the server when the command execution is completed.

In a traditional structural laboratory, a test can be suspended, resumed, or even stopped prematurely for various reasons such as safety concern or the necessity of minor specimen adjustment. On PNSE, FCM still has full privilege to change its running state if necessary. However, to the end of an event reflective platform, the FCM is obligated to send a notification to the server to flag any change of its state.

Signals and Command Cycle

Signals on PNSE are referred to those values that change continuously with respect to time. Any variable values in both CGM and FCMs, such as sensor values measured by FCMs in the laboratories, structural responses calculated by a numerical integration algorithm in the CGM, are regarded as signals on PNSE. On PNSE, signals are divided into two categories: the "critical signals" and the "open signals." Critical signals refer to those signals that are critical to the progress of the collaborative experiment such as the command and restoring force responses in a pseudo dynamic test. They are prerequisites to complete a cycle of command execution and actually guide the progress of the test. The open signals refer to those selected signals that are to be publicized on the Internet. PNSE client publicizes the open signals by sending them to the server, which in turns stores them in a database on the Internet for data storage and real time display. Open signals are very valuable for purposes of test monitoring and understanding of the specimen structural behaviors.

The CGM virtually initiates a “command cycle” which means a cycle encompassing those actions to be executed before the next command is generated. The FCMs also play prerequisite roles to complete a command cycle. The whole collaborative experiment is actually done by repeatedly executing a number of the command cycle.

Human Communication

On PNSE, human communication is still necessary but not as easy to implement as in a traditional structural experiment since all the staffs and operators of PNSE client programs are scattered at different locations around the world. To address this issue, a feature of instant discussion is included in PNSE. After successfully logins onto the server, all clients can actively send or passively receive human readable texts as a mean of communication. This feature provides convenient conversation channel for human communication and is a necessity since it is almost impossible to define all events possible that can occur in the course of the test in the application protocol.

THE APPLICATION PROTOCOL - NSEP

Overview

The TCP/IP suite provides reliable data transmission without knowing the actual content of the data. The content of the transmitted data should be understood by both sides of a connection; hence, an application protocol must be defined at the application level. For the server and all clients to work collaboratively on PNSE, they must have a well-defined application protocol as a common language to communicate. An application protocol “NSEP” is proposed to work with PNSE. NSEP defines the communication rules and data packets to hold signification information for PNSE. The PNSE server and clients communicate to each other by sending and receiving those pre-defined data packets over the Internet. The PNSE server and client notify the peer on the other end of the connection that something has happened by sending appropriate NSEP data packets.

Data Packet

NSEP data packets contain useful information relevant to the collaborative experiment and are composed of parameters of some defined primitive data types. The detailed description of those defined packets can be found in Tsai [8]. NSEP is designed intended to make PNSE an event reflective platform. All significant events that can occur in clients and information that is relevant to the progress of the collaborative experiment have been defined to realize an event-reflective PNSE.

Active Notification

NSEP stipulates that both the PNSE server and all clients should take the responsibility of making active notification to all other participants if it owns the information relevant to the progress of the collaborative experiment. For example, if an FCM needs to hold the experiment for any reason, it should notify the PNSE server before or immediately right after it really does it. When the server receives this notification, it has the responsibility to notify all other clients. NSEP stipulates this active notification to simplify the communication over the networks and to enhance the communication efficiency.

The concept of "event-driven" is the modern philosophy of programming and is powerful when the sequence of computational works can't be determined by the programmer in the coding stage of the program. This is exactly the case of collaborative experiment and hence NSEP is developed under the concept of event-driven. In other words, there is not a "processing center/module" which controls the contents and sequence of works. The PNSE server does not mandate any client to do particular tasks. The progression of the test is led by continual actions responding to events triggered by all clients. The concept of event-driven actually constructs PNSE a true cooperating platform since the server and all the clients take part of the responsibility of the test progression. In addition, combined with the concept of object-oriented programming, the characteristic of event-driven has great values especially when events and interactions in the system get more and more complex as time goes by.

Programming Issues

Communication on PNSE is full duplex transmission. This characteristic naturally rises from the fact that it is possible for sending and receiving actions to occur at the same time. It is evidently unable to completely determine the timing and the sequence of networked events. Due to the nature of uncertain network communication on PNSE, the event-driven architecture should be a better choice for client program development.

EXPERIMENTAL VALIDATION

One-Site Experiment on a Buckling Restrained Braced (BRB) Frame

The BRB frame was tested in NCREE laboratory (NCREE Lab.) to investigate the energy dissipation performance of the BRB components, which is described in detail in Tsai [12], and to evaluate the preliminary feasibility of the proposed PNSE. The schematic design drawing and the photo of the specimen are shown in Figs. 2 and 3. Four actuators were employed to impose the displacement commands on the SDOF system. A “master-slave” control algorithm was used to avoid unexpected and additional moments imposed on the specimen. In such a control algorithm, only one actuator (the master) ran in displacement control mode, while the other three (the slaves) ran in force control mode. The commands for the master were calculated by the CGM and received from the server through the Internet. The commands for the slaves were the force feedbacks of the master.

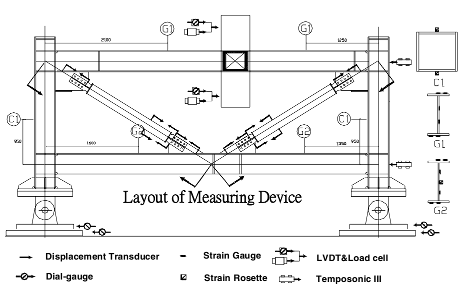


Fig. 2 Design drawing of BRB frame

Fig. 3 Installation of BRB frame in NCREE

The server ran on one computer in University of California-San Diego (UCSD in USA) and the CGM ran on one computer in NCREE, while the FCM ran on another computer in NCREE Lab.. The mass and damping ratio of the SDOF system were assigned as 760 tons and 1%, respectively. The 1999 Chi-Chi earthquake (TCU075) ground accelerations were used as the excitation with the PGA scaled to 0.06g. Integration time step size and ground acceleration duration were 0.02 and 30 seconds, respectively.

The displacement time history and the force-deformation relationships of the PSD test are shown in Figs. 4 and 5, respectively. The entire test consumed about 41’03”, which is considerably reasonable compared to a traditional PSD test. The test results indicate that all data packets were transmitted correctly when the test was in progress. The network event log also shows that the platform can correctly display the running state of the FCM and CGM. The preliminary test results confirm that extending the concept of PNSE into the actual application is doable and successful.

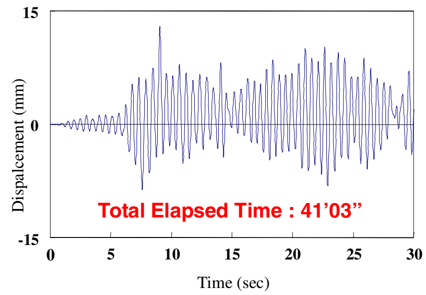


Fig. 4 Displacement time history of networked PSD test on BRB frame

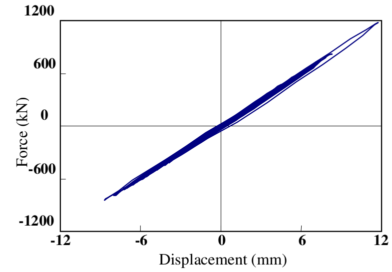


Fig. 5 Force-deformation relationship of BRB frame

Two-Site Experiment on a DSCFT-Bridge

To verify the validity and efficiency of the proposed PNSE, a series of transnational collaborative experiments were conducted on a two-pier bridge system. Fig 6 shows the numerical model of the reduced scale bridge system with one rigid superstructure and two DSCFT piers (C1 and C2) fixed-connected to the ground. Fig. 7 shows the photos of two DSCFT piers, C1 and C2, which were fabricated and tested in NCREE laboratory (NCREE Lab.) and in National Taiwan University laboratory (NTU Lab.), respectively. Suppose that the flexure deformation would not be induced in the rigid superstructure, and that each pier, which is hinge-connected to the superstructure, only has a longitudinal (NS or X) and a transverse (EW or Y) translations. Hence this model has 4 DOFs in total, which are assigned at the top of the two piers. The span is 6m in length and the height of each pier is 2.37m. DOF 1 and 3 were lumped with a mass of 507.2ton; DOF 2 and 4 were lumped with a mass of 235.6ton. The stiffness of each pier assigned in the pure numerical simulation was calculated by the linear regression of the experimental hysteretic loop within the elastic range. To simulate the effects induced by the frictional forces in tests, 2% and 5% damping ratio were assigned in the pure numerical simulation for piers located in NCREE Lab. and NTU Lab., respectively. The detailed information of the design of the columns can be found in Tsai [13].

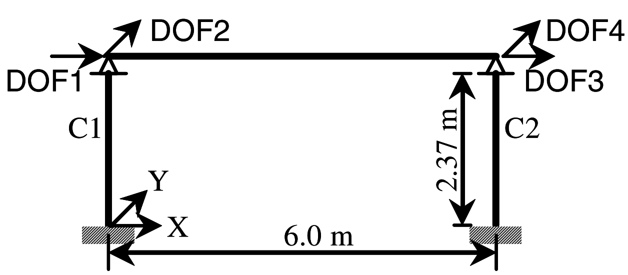


Fig. 6 Simulated bridge system model

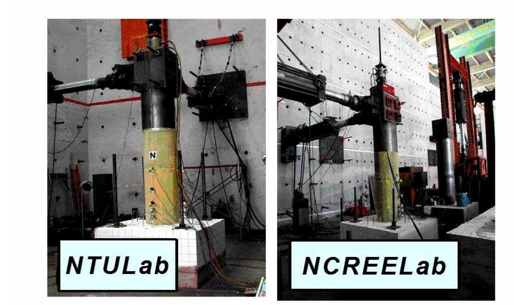


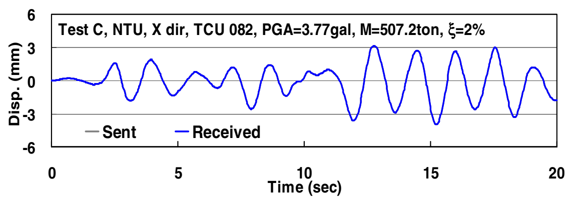
Fig. 7 Installation of DSCFT piers in NTU and NCREE

The TCU082 NS accelerations (The ground accelerations recorded in TCU082 station in the NS direction during 1999 Chi-Chi Taiwan earthquake) with the PGA scaled to 3.77gal were applied in the X direction, while The TCU082 EW accelerations with the PGA scaled to 9.13gal were applied in the Y direction. S_a (T=1) = S_a^D /3/15 = 0.4g/3/15 = 0.00889g is considered. The time duration was 20 seconds, and the integration time step was 0.02 seconds. A constant axial force was applied on the top of each pier to simulate the vertical load sustained on the piers.

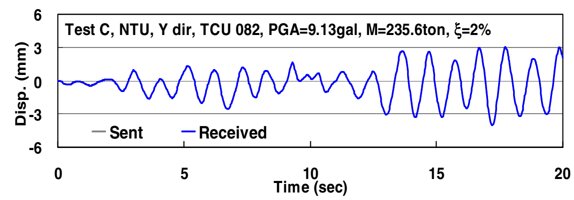
The control systems employed in NCREELab and NTULab are MTS FlexTest IIm system and MTS 407 controllers, respectively. The FCMs in NCREELab and NTULab are built by C++ programming language and LabVIEW, respectively. Both FCMs ran on Microsoft Windows 2000 operating system.

Three PSD tests (Test A, B, and C) were conducted on the specimens. All the testing parameters are the same among these three PSD tests except for the locations of the PNSE server and the CGM. In Test A, both the server and the CGM ran on the same computer in NCREE. In Test B, the server was located in NCREE while the CGM was in Stanford University in USA. In Test C, the server was resided in Stanford University in USA; meanwhile, the CGM was placed in NCREE.

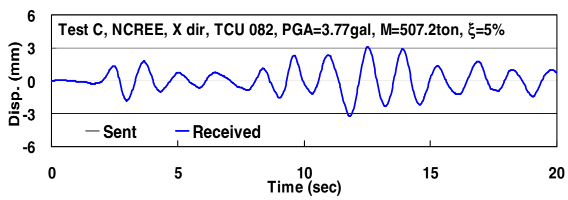
Fig. 8 shows the comparison between the commands generated by the CGM and the command received by the two FCMs. It is evident that commands were correctly transmitted on PNSE. The displacement time histories and the comparisons between the test results and numerical simulations are illustrated in Fig. 9. The test results indicate that the experimental responses are in good agreement with the numerical analytical predictions. This further proves that all signals, including the commands and critical responses, are correctly transferred between the server, CGM, and FCMs on PNSE.



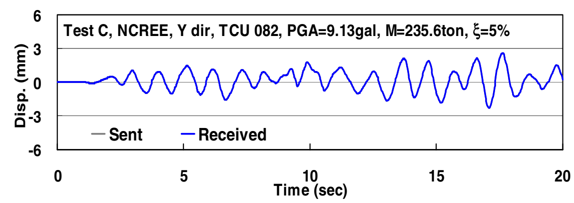
(a) X direction in NTU Lab.



(b) Y direction in NTU Lab.

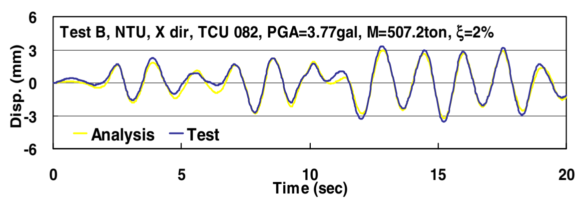


(c) X direction in NCREE Lab.

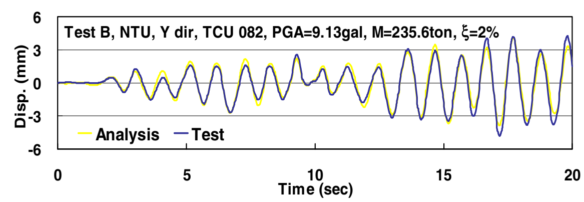


(d) Y direction in NCREE Lab.

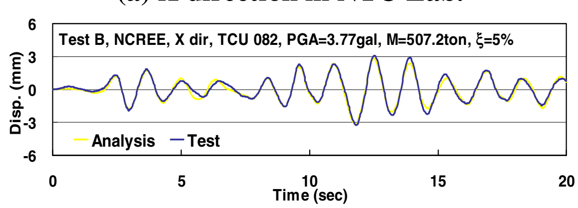
Fig. 8 Sent and received command time histories of Test C



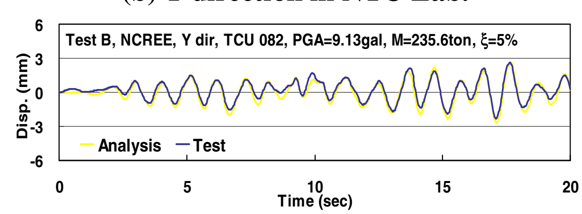
(a) X direction in NTU Lab.



(b) Y direction in NTU Lab.



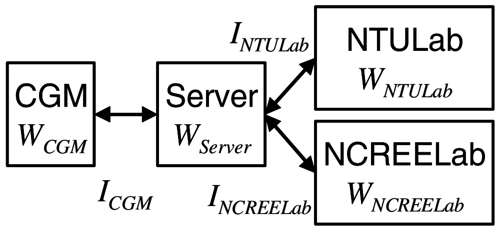
(c) X direction in NCREE Lab.



(d) Y direction in NCREE Lab.

Fig. 9 Experimental and analytical displacement time histories of Test B

The efficiency of PNSE can be investigated thoroughly by recording the time consumed in each process as shown in Fig. 10. First, the CGM generates the displacement commands (W_{CGM}) and then conveys those to the server through the Internet (I_{CGM}). After processing those command packets (W_{Server}), the server simultaneously dispatches those to the FCMs in NTU Lab. (I_{NTULab}) and NCREE Lab. ($I_{NCREELab}$) over the Internet. After the FCMs impose the displacement commands on specimens and measure the force signals in both laboratories (the maximum of W_{NTULab} and $W_{NCREELab}$), the measured forces are sent back to the server on the Internet (the maximum of I_{NTULab} and $I_{NCREELab}$). The server processes those force packets (W_{Server}) and sends those packets to the CGM via the Internet (I_{CGM}). At this time, the next displacement commands can be derived by the numerical integration in the CGM. This procedure would be iterated until the excitation duration is terminated.



W_x :working time of module x

I_x : Internet time (round trip) between module x and server

$T_{total} = W_{CGM} + I_{CGM} + W_{Server} + \max.[(I_{NTULab} + W_{NTULab}), (I_{NCREELab} + W_{NCREELab})]$

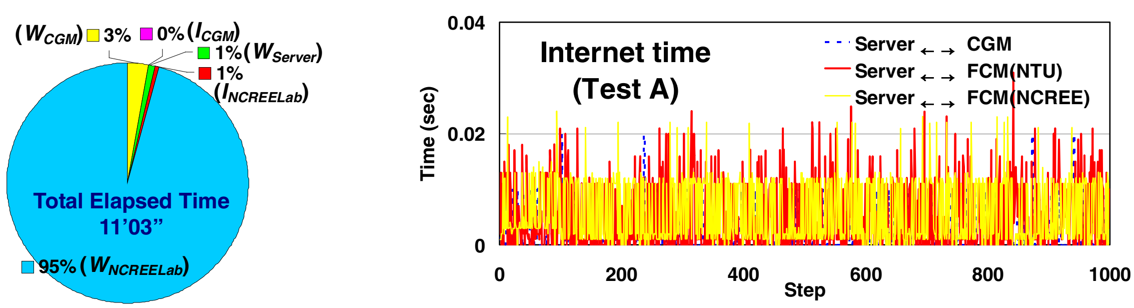
Fig. 10 Time distribution flowchart

Statistics of the average time consumed in tasks within each program and data transferring over the Internet for each step, as well as the time needed for the Microsoft Ping program, which was performed as a "benchmark" for the comparison purpose, are listed in Table 1. The time distribution diagrams and the Internet time histories for each test are illustrated in Fig. 11. Obviously, the time consumed in the communication over the Internet varies proportionately with the Internet route between nodes of the network. The results indicate that in the case of one node (the server or CGM) was resided in Stanford University in USA, the internet time was about 0.16~0.17 seconds for each step, whereas that in Test A (both the server and CGM were in NCREE in Taiwan) was less than 0.01 seconds. The time consumed in transmitting data packets on the internet were 1%, 21% and 32% of total elapsed time in Test A, B and C, respectively. The majority of the entire time in each test was consumed in the working of the FCM (95% in Test A, 77% in Test B and 63% in Test C).

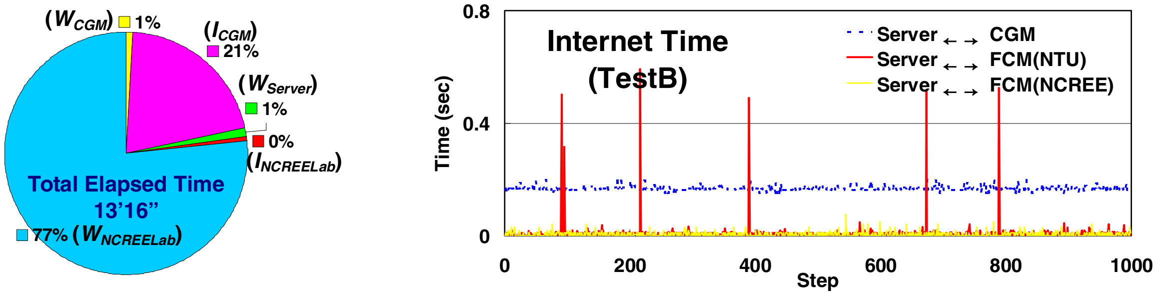
Table 1 Time statistics on PNSE

Activity	W_{CGM}	I_{CGM}		W_{Server}	I_{NTULab}		W_{NTULab}	$I_{NCREELab}$		$W_{NCREELab}$	T_{total}
		PNSE	Ping		PNSE	Ping		PNSE	Ping		
Test A	**0.0180**	**0.0080**	**<0.001**	**0.0437**	**0.0037**	**<0.001**	**0.5512**	**0.0046**	**<0.001**	**0.6356**	**0.6634**
Test B	**0.0060**	**0.1661**	**0.1628**	**0.0096**	**0.0056**	**<0.001**	**0.5486**	**0.0039**	**0.0070**	**0.6106**	**0.7963**
Test C	**0.0153**	**0.1693**	**0.1653**	**0.0459**	**0.1651**	**0.1625**	**0.6071**	**0.1701**	**0.1608**	**0.6540**	**1.0545**

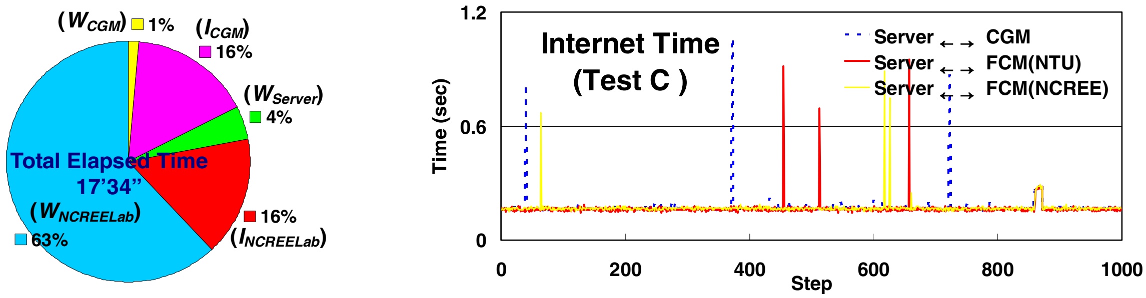
Note: 1.Time is recorded in unit of (sec/step).
2. Internet time indicates time needed for a round trip.



(a) Test A (Server in NCREE, CGM in NCREE, and FCMs in NCREE and NTU)



(b) Test B (Server in NCREE, CGM in Stanford University, and FCMs in NCREE and NTU)



(c) Test C (Server in Stanford University, CGM in NCREE, and FCMs in NCREE and NTU)

Fig. 11 time distribution diagrams and Internet time histories for each test

By comparing the data transmission time on the Internet among these three tests, it is very obvious that for the worst case (Test C, data transmission between NCREE Lab. and the server), it costs 0.1701 seconds, or 16% of time consumed for each step to transfer data packets. However, it is considerably satisfactory compared to the Microsoft Ping program (0.1608 seconds). For each step in test C, only about 0.3394 (I_{CGM} + max.(I_{NTULab}, $I_{NCREELab}$) = 0.1693 + max(0.1651, 0.1701)) seconds is needed for transmitting data packets between Taiwan and USA. Hence, the Application Protocol Approach exhibits rather satisfactory working efficiency. The Internet time history in Fig. 11 indicates that the transmission is fairly stable even if only a few spikes are observed, no matter in the transnational or domestic test. In a word, it can be concluded that PNSE exhibits satisfactory efficiency on data transferring and program processing.

One-Site Experiment on a CFT/BRB Composite Frame

Another series of networked PSD tests, which were performed on a full scale 3-story 3-bay CFT/BRB composite frame using PNSE (Chen [14]), further prove that PNSE is practicable on networked collaborative tests. The photo of the specimen is shown in Figs. 12. Although only one FCM (the NCREE Lab.) was involved in the experiments, PNSE was still employed not only for near-real-time display of experimental data, statuses, and video images, but also for verification of the characteristics of environment independency and the ability of event reflection. In these tests, a FreeBSD-based CGM resided in NCREE was used for the numerical integration procedure. Fig. 13 shows the typical windows displayed on the Internet (http://cft-brbf.ncree.gov.tw/) during and after the course of the experiment. It proves that applications running on different operating systems can be successfully incorporated into PNSE, as well as the statuses of the whole experiment and of all clients can be reflected correctly and promptly on PNSE.

Fig. 12 Installation of CFT/BRB composite frame in NCREE

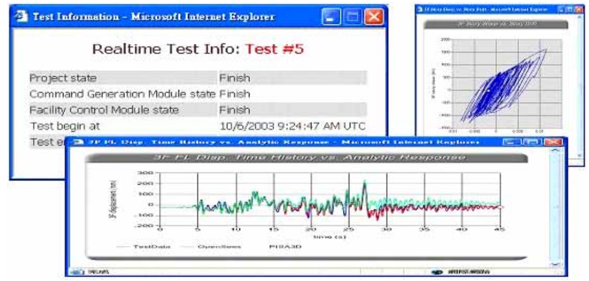


Fig. 13 Displayed windows on the Internet

CONCLUSIONS

Some conclusions are given in the following:

1. PNSE considers the completeness of the programming framework, the future development and combination of programs, and any event occurring in the proceeding of a test. Consequently, it's considerably comprehensive.
2. PNSE can be accessible regardless of heterogeneous facility control programs and operating systems because of the application of TCP/IP. The establishment of NSEP ensures that all significant events occurring in any real laboratory should be promptly "seen" by all other participating entities, Needless to say the accuracy and efficiency of data transmission. Explicit classification of control privileges of participants to use and share the experimental data not only can efficiently manage the operation of this platform, but also can prevent the risks of malicious attack.
3. It is worthy noting that any experiment through PNSE can be suspended, resumed or even stopped prematurely for various reasons such as safety concern or the necessity of minor specimen adjustment. Each laboratory control program can be able to have its own decisions to alter its own control running state, which is an effective mechanism.
4. At present, PNSE concentrates on core works directly related to the progression of networked collaborative experiments and excludes functionalities of data storage, management, monitoring, and video display, which can be implemented by utilizing commercially available software such as the Microsoft SQL server and the RealPlayer.
5. Applying the concept of active notification, "event-driven", make PNSE event-reflective and a true cooperating platform since the server and all the clients jointly take part in the responsibility of the test progression. That's to say, the progression of the test is led by continual actions responding to events triggered by all clients. This mechanism not only saves a lot of experimental time but also retrenches repeated frequent queries. Consequently, for the demand of our platform which is combined with the concept of object-oriented programming, an event-driven architecture should be a better choice to develop programs to be compatible with PNSE, although it is still possible to build programs under the traditional procedure-oriented programming architecture.
6. In the experiment with a large, complex or realistic specimen, the conventional PSD technique provides high speed at the cost of increased the capacity of laboratories. In contrast, the proposed platform, PNSE, is fairly efficient and economical. The test results indicate that on PNSE, the cost of increased time on the Internet is rather few and acceptable (for the worst case in the experimental validation, it is less then 0.1701 seconds to travel back and forth between NCREE in Taiwan and Stanford University in USA).

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