Remote-access real-time laboratory: process monitoring and control through the internet protocol

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Abstract The development of a remote-access real-time laboratory (RART-Lab) is described, and a case study is presented of its application to a real-time mechanical engineering experiment, namely a study of thermo-hydrodynamics of flow through mini-channels. (The study of such flows is vital for many applications, ranging from electronics thermal management to fuel cells.) The RART-Lab concept encompasses data acquisition during the experiment, storage, post-processing and online transmission of data to multiple users logged on to their respective web browsers. Control of the experimental process parameters (e.g. liquid mass flow rate and heater power level) from one (or more) remote stations over the web in real time is also incorporated. Online video images of the experimental facility, visualization modules and color-indexed temperature data can be transmitted by webcam. The system developed has a friendly graphical user interface. It also allows transmission of process parameter alarm signals via an e-mail client server or via an SMS text message to a mobile telephone. Simultaneously, conventional chatting has also been incorporated to add vibrancy to inter-user communication. In addition, three-dimensional computational fluid dynamics simulations have also been done simultaneously with the real-time laboratory to mimic the experiments. Such an integrated development greatly widens the possibilities of collaborative research, development, simulation and experimentation, to overcome the need for the physical proximity of the experimental hardware and experimenters. Such generic tools not only make academic interactions and real-time data sharing more fruitful but also greatly facilitate joint research and development activities between academia and the industrial community.

Keywords web-based engineering experiments; RART (remote-access real-time) laboratory

Introduction

With the complexity and interdisciplinary nature of emerging engineering designs and solutions, it is vital that groups working in industry and academia share information at a rapid pace, with the collective aim of increasing product quality and reducing development time and costs. The rapid growth of global internet connectivity, coupled with improved security norms and standards, gives us a powerful tool to achieve these goals. Complementing this need are computer-based data acquisition and virtual instrumentation, which are fast becoming a norm rather than an exception [1].

The web has become a vital element of all human activity. Arguably no other technology has made such an impact on modern humans than the internet. It forms one of the core foundations of a successful information-technology-based society. The web is used not only to gain visibility, share information, sell products and

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conduct business, but also to improve the way we design engineering systems, manufacture them and test the final products. A balanced usage of internet facilities can reduce the length of design cycles and improve overall quality [2].

The implications of such a networking technology can be far reaching. For example, using network technologies in measurement solutions, we can govern the input to and output from a hardware platform located on a production floor or test bench, deploy additional processing power for in-depth analysis in the control center via software support, log and store post-analysis information on a corporate database, and display key processed information to clients or consultants around the world via a standard web browser. Online feedback and corrective signals can be received and executed when desired. A smart and dependable partnership between the hardware and controlling software, working in unison, is vital for success. The technology greatly widens the possibilities for collaborative research, development and experimentation, as it overcomes the need for the physical proximity of the experiment and the experimenter.

Computer-based data acquisition, web-based experiments and virtual instrumentation and control applications have been an active area of interest in recent years [3, 4]. Similarly, researchers and educational groups have been working in the area of remote control suitable for classroom teaching. A special issue of *IEEE Control Systems Magazine* on wireless networks highlighted the importance of the subject [5]. Kumar *et al.* [6] reported a simple experiment involving the web-based transmission of data from a digital multimeter and a thermocouple. An internet-based control, monitoring and operation scheduling system for heating ventilation and air-conditioning systems was presented by Lin and Broberg [7]. More recently Canales *et al.* [8] have discussed the requirements for an adaptive and intelligent web-based education system.

In this context, the work presented here may help to meet the needs of higher education, where usage of interactive computer-based e-learning is on the rise. The proposed remote-access real-time laboratory (RART-Lab) allows, for example, university clients situated in remote locations to take advantage of experimental facilities that cannot readily be duplicated (e.g. for reasons of cost). This is especially attractive for developing nations. Recently, Zhuang and Morgera [9] have described the development of an internet-based instrumentation and control undergraduate course. The work reported by Regtien *et al.* [10] exemplifies the magnitude of interest in web-based systems – a consortium of 10 institutes from seven European countries have joined together to develop a multimedia internet-based platform on measurement techniques.

In this work we report the use of the web for core engineering education. The system described integrates a gamut of web technologies and allows not only for the transmission, via the internet protocol, to remote locations of real-time data generated on an actual engineering process/experiment, but also for the control of the experimental parameters in real time. Simultaneously, real-time video images can be transmitted by webcam; inter-user communication is done by conventional chat protocols. Successful implementation of the RART-Lab system, data collection under controlled conditions, post-processing, integration of simulation software as a ~~complimentary~~ appendage and comparison of collected data with available theoretical results are reported.

Experimental set-up

The primary aim of the experiment that we have used as a case study for the web-based RART-Lab is to understand the thermo-hydrodynamic characteristics of fluid flow in a mini-channel array. Such flow structures find wide application in fuel cells, electronic thermal management, compact heat exchangers, micro-reactors etc. The main parameters of interest are the differential pressure drop across the array and the spatio-temporal temperature distribution on the channel array walls and the fluid flowing inside it; these parameters allow calculation of the spatial or average Nusselt number. The data are required under different fluid flow conditions.

The experimental set-up is shown in Fig. 1 (which also shows the internet interface hardware architecture, described below). Fig. 2 shows the mini-channel test section. It consists of an array of seven parallel semi-circular mini-channels (D_{hyd} = 1.8 mm) machined on a copper plate 5.0 mm thick. A mica strip heater is attached below this copper plate to heat the incoming liquid flowing through the test section. A thermochromic liquid crystal (TLC) sheet along with a transparent polycarbonate sheet covers the top surface of the plate, as shown. TLCs react to changes in temperature by changing color. They have chiral (twisted) molecular structures and are optically active mixtures of organic chemicals; the TLC sheet turns from colorless (black against a black background) to red at a given temperature and, as the temperature is increased, passes through other colors of the visible spectrum in sequence (orange, yellow, green, blue, violet) before turning colorless (black) again at a higher temperature. The color changes are reversible on cooling. Thus, the local spatial temperature distribution can be suitably calibrated through RGB (red, green, blue) or hue–saturation–brightness scales [11].

The test fluid, at a fixed temperature, coming from a circulator bath at constant temperature, is allowed to pass through the mini-channel array via inlet and outlet headers. A digitally controlled variac controls the power supply to the heater (attached below the mini-channel array plate to heat up the water as it passes through). The streamwise spatio-temporal variation in the wall and fluid temperatures in each channel, depicted by the TLC sheet, is captured via a webcam. Fig. 3(a) shows a typical image of the TLC sheet (color original reproduced here in black and white). Additionally, the inlet and outlet temperature of the flowing liquid is measured by standard K-type thermocouples suitably located in the flow headers. Two more thermocouples are placed along the length of the mini-channel array for calibration purposes. A strain gauge pressure transducer, as seen in Fig. 1, measures the differential pressure across the channel geometry. The transducer requires an activation voltage of 10 V and generates a milli-volt signal corresponding to the differential pressure conditions. The stepper motor connected to the control valve regulates the flow rate of the test fluid to the mini-channel array by opening or closing the bypass valve fitted on the inlet line. The flow rate can range from laminar flows to turbulent flows ($200 < \mathrm{Re} < 3000$).

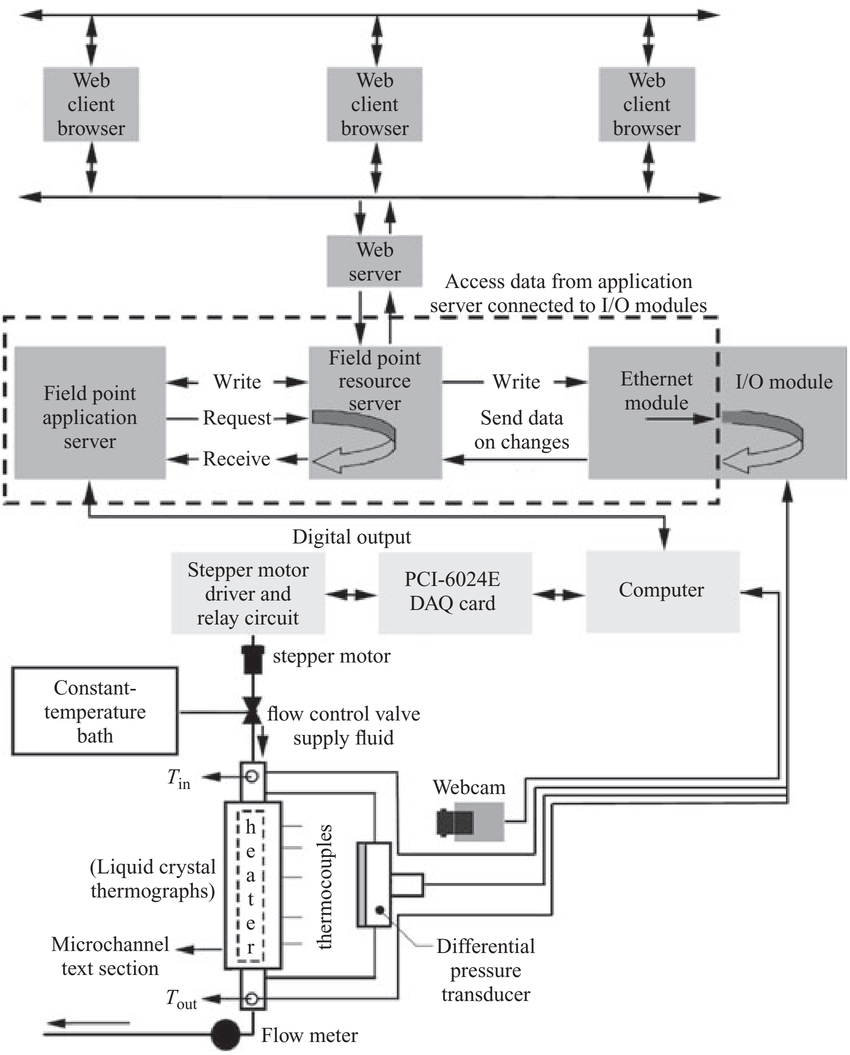

Fig. 1 *The RART-Lab system architecture.*

The primary aims of the experiment include:

- capturing the spatio-temporal image sequence of the activated TLC sheet for further analysis, leading to the estimation of the local spatio-temporal temperature (these data are post-processed to give the local and average heat transfer coefficient);
- measurement of temperature from the four thermocouples suitably located for the purpose of primary calibration and heat energy balance checks;
- measurement of differential pressure as a function of flow Reynolds number.

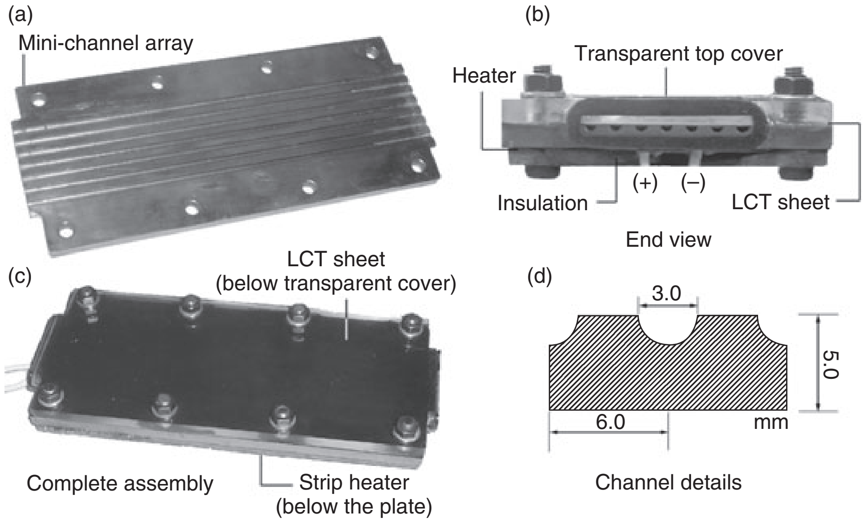

Fig. 2 *The mini-channel array test section: (a) top view of the array showing the seven channels; (b) end view of the array assembly; (c) photograph of the complete test assembly; (d) details of an individual channel.*

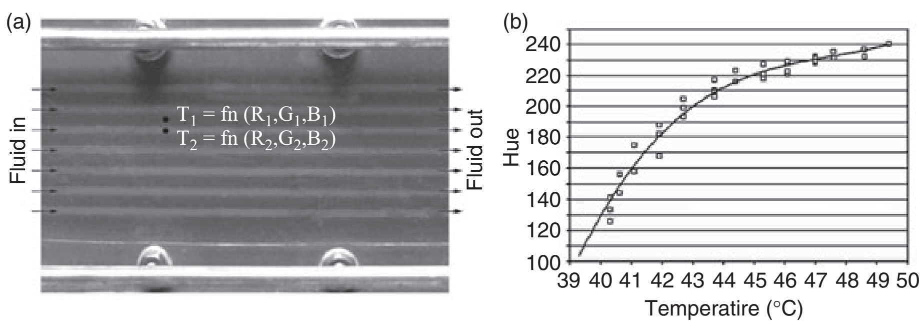

Fig. 3 *(a) Typical RGB image (reproduced here in black and white) of the LCT sheet depicting the spatial temperature distribution (transmitted via a webcam to remote locations); (b) LCT calibration curve between hue and temperature.*

The description here pertains only to the web interfacing of this set-up; the thermo-hydrodynamic data obtained from the mini-channel set-up will be reported elsewhere.

The RART system architecture

The experiment described above is integrated with the internet to create the RART-Lab environment. The complete system architecture of a typical web-based RART-

Lab process control application, including the experimental set-up described above, is shown in Fig. 1. It consists of the following basic elements:

(1) the primary process hardware/experimental set-up;
(2) a web server computer, which hosts the application and interfaces with the external world;
(3) a data acquisition/process server computer, which is capable of interacting with the web sever on one side and the process hardware on the other (simultaneous acquisition and online post-processing are possible);
(4) sensors, actuators and servo controllers connecting the process hardware to the process server via a suitable interface;
(5) embedded primary-system-level databases necessary for smooth process operation;
(6) remote client computers, which connect to the local web server through LAN/WAN for data acquisition, retrieval and feedback control of process parameters;
(7) mobile telephones/supporting networks for e-mail communication for the sending of alarm signals, if required, to many clients, who may be temporarily unconnected to the web server (these signals are generated by the process server in conjunction with primary databases, containing alarm parameters, and forwarded to the web server for further transmission).

The RART-Lab allows the remote user, connected through the internet, to fully access the graphic user interface (GUI) appearing on his/her web browser and to monitor the mini-channel flow experiment online. While the data acquisition still occurs on the on-site host computer, the remote user has complete control of the application. Individual web browsers, with permission, can initiate the measurement or automation application, as desired. The operator needs to log in, set certain pre-defined task parameters, and run the application directly. This is achieved via a common gateway interface (CGI). With the CGI, the user can communicate with a server-side program or script run by a hypertext transfer protocol (HTTP) server in response to an HTTP request from a web browser. This program normally builds HTML dynamically by accessing other sources, such as a database. Browsers can send the parameters to use in the application to the server. Other logged-in users can point their own web browsers to the same URL to view the real-time data (pressure, temperature, pictures etc.). To avoid confusion, the application is designed in such a way that only one remote client can control the application at a given time, but control can pass easily among various clients, with the permission of host. Simultaneously, conventional chatting and webcam facilities have also been incorporated to add vibrancy to inter-user communication.

The complete web-based application is designed to perform the following four major tasks:

(1) *Publishing data*. The application generates a static web report of test results that one user can share with others. This method is the electronic version of

the traditional printed report but has the advantage of easy access through a standard web browser.

(2) *Sharing data*. It expands the concept of publishing data to include transfer of the actual data between computers, such that users can perform different analyses or post-processing of the data, depending on their needs. Some applications might require streaming the actual data for additional processing, storage or monitoring. For example, a user can update out-of-bound parameters while the test is still progressing.

(3) *Remote control*. It expands the concept of sharing data to include enabling another computer to connect to the experiment and control that experiment remotely. For many applications, a test might be in a harsh environment or run overnight, such that it is inconvenient for someone to be at the terminal continuously.

(4) *Distributed execution*. The application has an architecture that shares the acquisition and analyses of the test results among several computers. Systems of the future will consist of measurement nodes that can transfer data between computers, so different parts of the test can run at different places, and the data can still be correlated and used to control other hardware items.

The above tasks are achieved with the hardware architecture described above; execution and control are by software support in a LabVIEW® environment. With the built-in web server in LabVIEW®, the front panel of the application can be published without adding any additional development time. Once the web server is enabled, LabVIEW® generates front panel images that can be accessed from any web browser. A typical computer panel at the host or remote location is depicted in Fig. 4. The following sections describe some of the main hardware and software components used in developing the RART-Lab.

System hardware framework

In the present context, quite a few commercial vendors offer 'real-time' (RT) hardware/software modules that can be used to develop remote laboratories. We have incorporated the functionality of process measurement and control in the RART-Lab through RT-series hardware (Compact Field Point cFP-RT device) and LabView®-RT software (see www.ni.com). With this framework it is possible to extend the possibilities of a simple PC to a networked, web-enabled system of intelligent nodes for process control and monitoring. This configuration was chosen so as to combine the tasks of data measurement, logging and control on a single RT platform rather than to use separate modules for these tasks, which may not be more efficient than a single integrated module. This integrated module is an easy-to-use, rugged and expandable industrial control and measurement system composed of multiple I/O and intelligent communication interfaces.

We have incorporated the ethernet network communication module (cFP-1804) as the 'resource server'. The cFP-1804 connects directly to ethernet networks, auto negotiating on it, depending on the applicable communication rates (e.g. 10 Mb/s or 100 Mb/s). It includes an RJ-45 connector for connection to 10BaseT and 100BaseTX

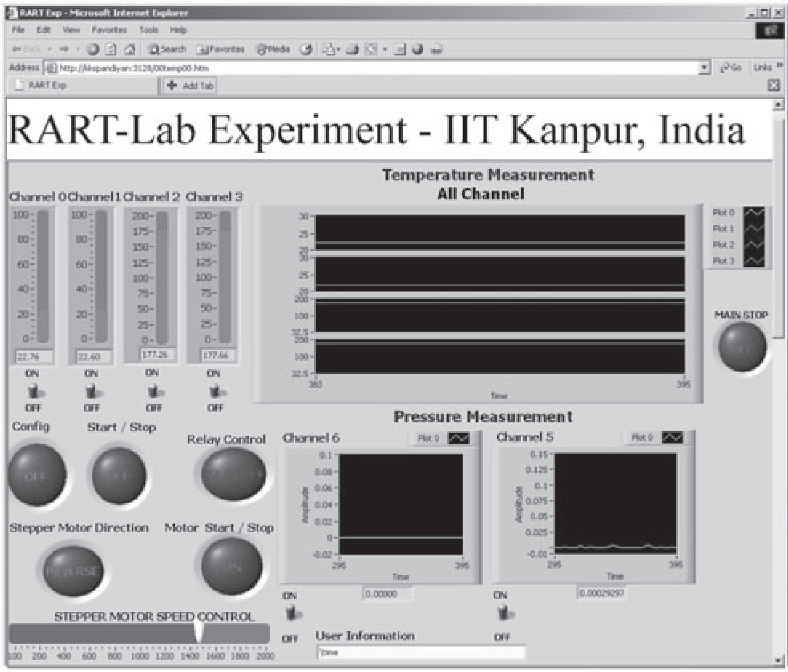

Fig. 4 *Computer panel at local host or remote client connected via the internet.*

networks, using a protocol based on standard transmission control protocol/internet protocol (TCP/IP) to maintain full compatibility with existing networks. The network interface monitors connected I/O modules and publishes I/O data only when the value changes. This ethernet module uses an asynchronous communication architecture, called as an event-driven communication, in which the network module (the field-point resource server) automatically sends updates to a client when data change. One advantage of an event-driven method, along with data compression, is that it avoids unnecessary ethernet traffic, thus maximizing communication efficiency. The resource server then caches the data from I/O modules and uses them to respond to read requests. The network module periodically sends and receives a time-synchronization signal so that it can adjust its clock and provide proper time stamping. When signals do not change over long periods, the client sends periodic resubscribe messages to verify that the system is still online.

The peripheral devices include a data-acquisition card, PCI-6024E (M/s NI Instruments), for the web-based control of stepper motors connected to the liquid flow control valve attached to the mini-channel set-up (see Figs 1 and 5). The stepper motor has a rating of 6 V, 1.8 A, a holding torque of 1200 mNm with a stepping angle of 1.8º. Both the speed and direction can be changed at any instant by applying the appropriate codes at the stepper motor's signal lines. To drive the stepper motor, a signal conditioning stage is needed, as shown in Fig. 5. Since the output

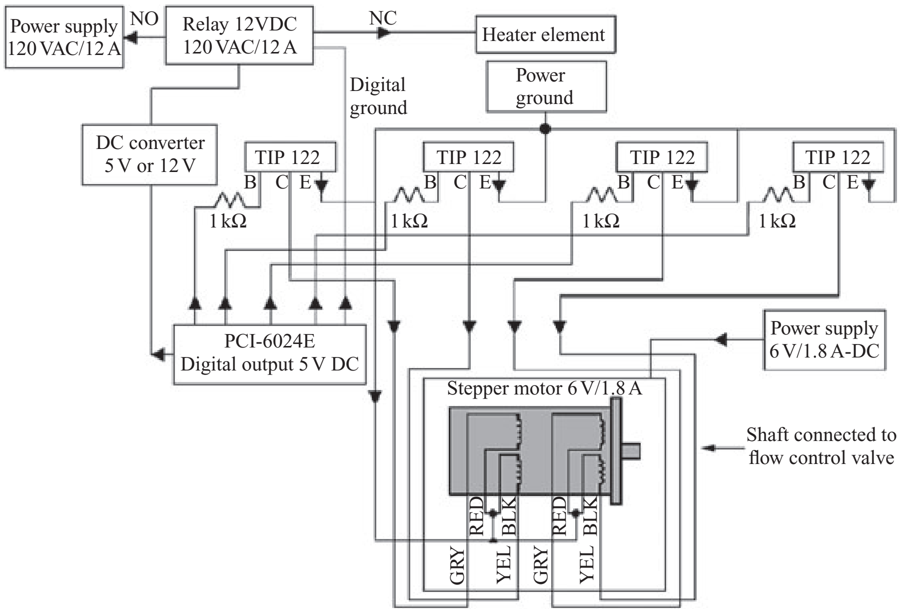

Fig. 5 *Stepper motor for inlet flow control of the liquid and the heater relay driver circuit.*

of the DAQ used (the PCI-6024E) was too low to drive the motor, a current amplifier (line driver regulator) was connected between the DAQ digital output and the motor wires. Using the TIP 122 line driver regulator, the motor can be driven. Toggle (on/off) control of the heater power input element was achieved with switching relays of 12 V (DC), 2 A, by utilizing the digital output, 5 V (DC), of the DAQ card.

System software framework

The system software framework architecture is illustrated in Fig. 6. It is centered on Application Development Environments (ADE, viz. LabVIEW and LabWindows). Drivers for the RT series field point module and PCI-6024E DAQ card are directly interfaced to the ADE to tightly couple the native hardware capabilities with the flexibility of the software environment. These software capabilities provide a host of tools with which a completely customized application can be built. The measurement and control tool (MCT) kits included in the platform provide the process control and monitoring capabilities. It uses the field point assistant library to access and acquire the signal directly from the sensors. It also provides common measurements such as I/O operation, read/write data with timestamp and so on with a change in the signal data. Available library functions include basic mathematical/logic operations and Boolean functions, such as digital output signal for relay control and

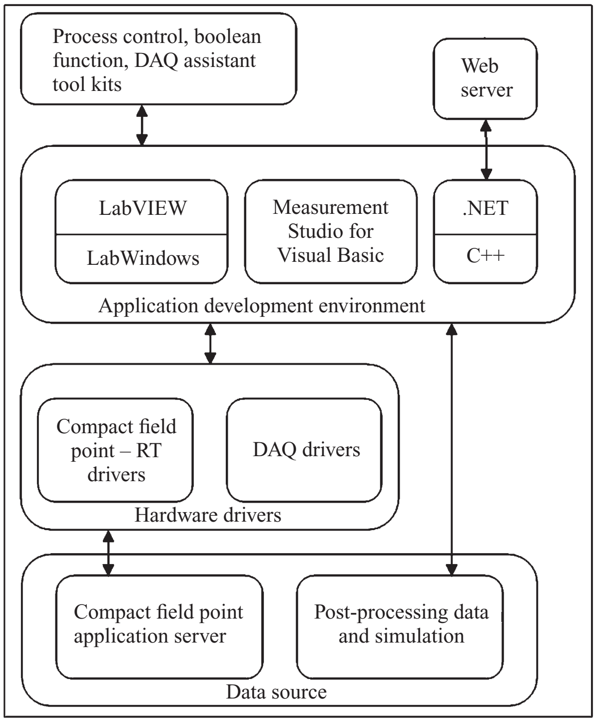

Fig. 6 *System software framework architecture.*

stepper motor control. Building efficient simultaneous capabilities for analysis directly into the application server eliminates the need for post-acquisition analysis.

The web server, based on the component object model (COM), is part of the Microsoft®.NET Framework®. It uses the .NET Framework to provide plug-and-play connectivity and interoperability between disparate automation devices, systems and software, both on the server floor and on the client floor. The use of PC-based standards such as TCP/IP and OLE process control (OPC) makes real-time floor information easily accessible to the online applications.

Functional deployment of RART-Lab

The experiment to study the thermo-hydrodynamics of developing flow through a mini-channel array by LCT, as described earlier, has been systematically conducted through the RART-Lab interface at our institute. Although many simulations and experimental runs on RART-Lab have been performed, we report here only this one typical example as a representative case study.

It is a fact that, compared with the use of sophisticated and expensive experimental hardware, the penetration of personal computers and simulation packages is much deeper and popular in academic institutions of many developing countries. Against this background, one feature that we believe greatly enhances the utility and impact of real-time laboratory concepts (RART-Lab) is the integration of numerical simulation of experiments. The idea here is that students can run the computational simulation as well as the real-time experiments simultaneously (or in succession), to maximize the pedagogical impact of the exercise. The limitations and possibilities of both these exploratory techniques, simulation versus experiment, can thus be explicitly emphasized. In addition, the scope and range of computational simulations ('numerical experiments') can be widely expanded, without material costs, once a set of actual experiments have been conducted and validated. With this philosophy, in addition to the experiment described earlier, a three-dimensional (3D) computational grid mimicking the actual experiment, including all its boundary conditions, was also set up, in a Fluent® environment.

The students were asked to develop a simple 3D unstructured grid computational domain for the actual experimental set-up (one channel), as shown in Fig. 7. Fig. 7(a) depicts this computational domain; the simulated boundary conditions correspond to those of the actual experiment. After grid validation and grid independence tests had been carried out on benchmark solutions, simulations were done for Re = 1080 and Re = 3210, at an input heat flux of 6790 W/m^2 given to the bottom heater. The inlet fluid temperature was kept at 316 K. Fig. 7(b) shows the average wall and fluid temperatures for these two sample case studies. As can be clearly seen from the wall temperature profiles, under laminar flow conditions (Re = 1080) the flow is largely developing in nature, while under turbulent conditions (Re = 3210) the flow develops rather quickly [12]. This fact can also be seen by observing the simulated temperature contour results in Fig. 7(c). Also, this result exactly corresponds to the RART-Lab experiment where the same data are generated by the actual LCT.

Controlled experiments were performed by a group of students at remote locations via the RART-Lab platform on the mini-channel array. After post-processing of the data, which includes online calibration of the LCT images (see Fig. 3(b) for a typical calibration curve obtained), the local Nusselt number along the length of one channel has been plotted in Fig. 7(d). The experimental data obtained via the internet-based experiment have been compared with both CFD-simulated results and those generated by standard available representative correlations for developing laminar and turbulent flow conditions for circular ducts (i.e. the Phillips correlation and the Shah and London correlation [12, 13]). As can be seen, the match is quite satisfactory. Thus, we have been able to establish the methodology of simultaneously conducting/controlling actual hardware-based experiments via RART-Lab, using the internet protocol, CFD simulations of the conducted experiments, and post-processing of the data generated.

Summary and conclusions

The complete mini-channel flow experiment along with the coupled RART-Lab has been successfully demonstrated at our institute. The acquired pressure, temperature

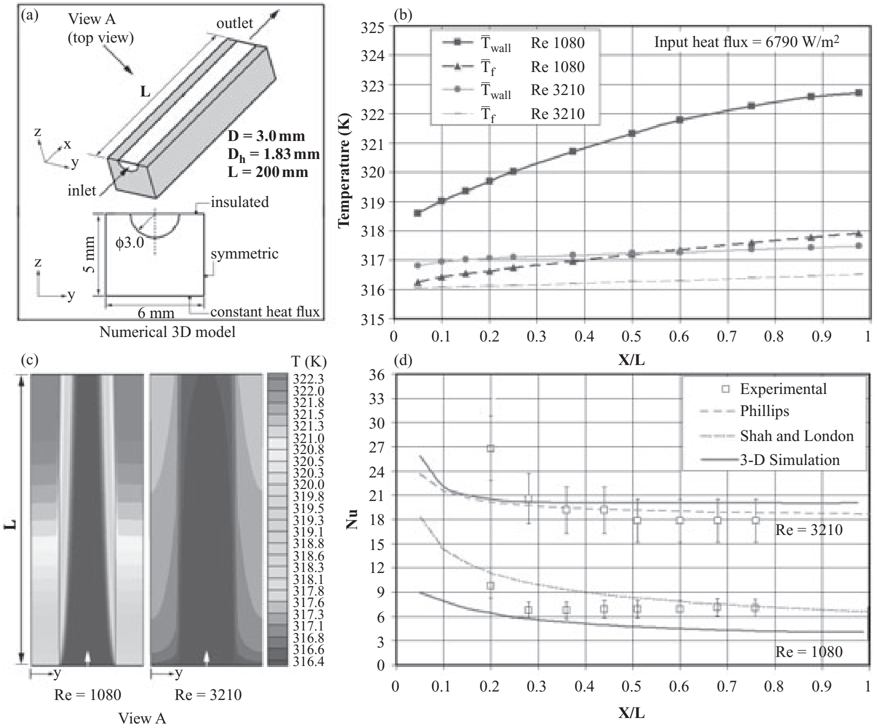

Fig. 7 *(a) Computational model of the experiment – developing flow through a semi-circular mini-channel. (b) Numerical solution of the wall and fluid temperature at Re = 1080 (laminar) and Re = 3210 (turbulent). (c) Spatial temperature contours of wall and fluid from the top view (view A, part a). (d) Nusselt number variation under developing flow conditions at Re = 1080 and Re = 3210 – comparison of experimental data with simulation and two correlations applicable under these conditions [12].*

and visual data were made available in text as well as graphical formats to multiple logged-on users. The streamwise spatio-temporal variation of wall and the fluid temperatures in each channel of the multi-channel array, under different inlet boundary conditions, was captured via a webcam (i.e. a color image of the TLC sheet, as in Fig. 3(a)) and transmitted via the internet. Alarm signals were generated by e-mail whenever the inlet/outlet temperature of the fluid crossed the set point. Simultaneously, the experimental conditions have been simulated on commercial CFD software. The experimental heat transfer results obtained via RART-Lab have been successfully compared with the simulations and standard available correlations in the literature for the given conditions.

The web is changing the way we take measurements and distribute results. Many different options exist for publishing reports, sharing data and remotely controlling applications. We have implemented this simple yet powerful concept for real-time engineering education and research. With the technology presently available, we can incorporate the web into many different aspects of our application, from simply sharing the data with colleagues to creating a unique, powerful, distributed application, combining different measurement nodes and multiple computers together in one robust measurement and control system. The project reported here is one step towards that goal.

It is apt to emphasize that transmission and control over the internet require sound internet security measures to be in place. Unless these issues are properly addressed, corporate clients, in general, will shy away from using internet-based experiments and sharing real-time critical data. Also, the speed of connectivity of different clients with the host will determine the time lag in execution of the control signals. This can become a serious issue if real-time control algorithms are to be implemented.

It is believed that a generic system such as that demonstrated in this work not only will make academic interactions and real-time data sharing more fruitful, but also can facilitate collaborative research and development activities. The system is also suited for India as well as other developing nations, where there are typically many distributed networks of engineering colleges/institutions, but all such institutions cannot afford to install large hardware intensive experimental set-ups.

Acknowledgements

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