

Web-Based Collaborative Learning Architecture for Remote Experiment on Control of Bioreactor's Environment

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Abstract — The unprecedented growth in Internet technologies has created revolutionary changes in collaborative working in an on-line environment with round the world accessibility. The adoption of collaborative learning tools with remote laboratory enhances the experiential learning aspects of engineering education. This paper presents a collaborative learning and remote experiment on the control of a bioreactor environment by establishing communication between the process control computer and remote users through the Internet. The software application is developed using graphical programming tools to control the process parameters and to set the control constants associated with the PID control system. The LabVIEW virtual instruments transfer information to web clients is performed using web server and standard internet browsers for data access. Multimedia features are added to the architecture to supplement the teaching and learning activities. The proposed system structure and functionalities tend towards the translation of traditional collaborative characteristics into an Internet based on-line collaborative learning environment.

Index Terms—Collaborative Learning, Bioreactor, Virtual Instruments, PID control, Web-server, Data Acquisition.

I. INTRODUCTION

Laboratories play a paramount role in technical education and the Internet based remote laboratories influences the possibility of distance learning of different disciplines in engineering. The demands of a good on-line collaborative learning environment include friendly access, near real-time operation, visual access, signal feedback and efficient utilization of the available bandwidth. Developments in communication technologies have provided new possibilities and new challenges for designing and deploying collaborative environments for remote engineering applications [3].

There are various approaches in literature which describe the remote laboratories on electrical and electronic circuits [2] [15], microcontrollers [10] and robots [14]. In most of the real-time remote experimentation system uses the graphical programming

tools and data acquisition system to interface the laboratory experiments with the server and remotely accessible virtual instruments are designed for control and display of the experiment parameters [7][8]. Design of on-line learning environment requires various elements to deliver instruction, facilitate interaction and to enhance the quality of learning [1] [9]. The collaborative learning tools provide a chance for learners to interact with a trainer or other user and it adopts group learning format. The use of MS NetMeeting offers online tools such as email, chat rooms, discussion boards and file sharing can be used to supplement the teaching and learning activities [6]. Many researchers use these tools to create more effective learning environment in order to improve efficiency in terms of speed and collaboration [5]. The developed system integrates remote laboratory experiments with the collaborative learning tools facilitates the on-line course delivery more effective.

The paper describes the extension of remote laboratory concept to the process control operations of a bioreactor. The objective of the experiment is to understand the process operation and control the process parameters: temperature, pH and agitation speed. The Virtual Instruments (VI) are developed using LabVIEW, to display the process variables, set the control parameters and to indicate the resulting control action of the bioreactor process. The National Instruments (NI) data acquisition hardware PCI6251, and Educational Laboratory Virtual Instrumentation Suite (ELVIS) [21] and the custom designed signal conditioning circuits interfaces the different components of a bioreactor's unit with the web server. The VI control algorithms are developed to process the sensor inputs obtained through data acquisition system and generate the control actions based on the user set value of the parameter. The control strategies are implemented using PID (Proportional, Integral & Derivative) control algorithms developed using graphical tool, which produce an acceptable control for most of the process operations. The user friendly Graphical User Interface (GUI) developed using LabVIEW virtual instruments can be accessed through

the web, which facilitates the on-line access and control of process parameters. A web camera with audio inputs interfaced with the web server transmits audio and video signals to the client in real-time enabling the remote user to experience the real environment.

II. SYSTEM ARCHITECTURE

The architecture model which fits into the designing of collaborative learning environments is the client-server architecture that facilitate multi-user e-learning environment. Instructional support is an important element in remote learning which can be accomplished by establishing communication between a tutor and the remote clients using synchronous or asynchronous communication tools [16].

Fig. 1 illustrates system architecture to establish a collaborative e-learning environment for remote laboratory experiment on control of bioreactors environment. The architecture proposes that the collaborative working on remote laboratory application consists of Web-server, Web-based user-interface, Signal conditioning unit, graphical control system, multimedia features and the experiment.

A. Web Server

The web server is primarily used for data acquisition, measurement and control operations, which is configured by LabVIEW [11]. The LabVIEW programs are called Virtual Instruments, are developed and converted to HTML (Hyper Text Markup Language) page and are stored in the root directory of the server. The VI's of the corresponding experiment is mentioned in the VI access list and the IP addresses of the client machines are mentioned in the browser access list of the server. The graphical interface to the client side is developed by creating a HTML page of the VI, which includes the visual display of control commands, meters for measurement and graphs to record readings of the experiment. The benefits of the LabVIEW web server are: shortest development time, best user handling for the clients run on windows, Linux Mac and with nearly every browser. At the client side, LabVIEW run-time-engine has to be installed.

B. Web-based User Interface

The clients are distributed throughout the network are mediated by a conventional web browser such as Microsoft Internet Explorer or Netscape. The application programs are developed in LabVIEW and stored in a web server. The system developed using LabVIEW offers several methods for remote access using TCP/IP protocol without additional programming. VI consists of an interactive user interface named front panel and a source code in the form of block diagram. The VI can be included in an HTML file, which can be created either manually or using LabVIEW web publishing tool and is stored in the root directory of the server. The user may access any of the HTML pages saved at root directory of web server.

C. Signal Conditioning Unit

The signal conditioning is the electronic circuitry which interfaces the physical components of the experiment with the web server. It receives the weak electrical signals from the temperature and pH transducers and converts it in to suitable range which can be processed by the data acquisition present at the server. The graphical code processes these signals using PID control algorithms developed using VI and generates control signals which are available at the ELVIS output ports. These signals are further processed by the signal conditioning unit to match the electrical parameters of data acquisition system with that of actuators present in the physical laboratory.

D. Graphical PID Control System

The basic function of the controller is to execute an algorithm (electronic controller) based on the control inputs (coefficients), the desired operating value (set point) and the current process value. In most cases, the controller requirement is to make the process value as close as set point. One of the generic control strategies is the PID control algorithms, which is developed to control the bioreactor process parameters using graphical code. The PID control algorithm is used for the control of almost all loops in the process industries and is also the basis for many advanced control algorithms. The PID controller has to maintain the output at a level so that there is no difference (error) between the process variable (P_v) and the set point (SP). The PID control algorithms are implemented in LabVIEW VI using separate sub VI's for Proportional (P), Integral (I) and Derivative (D) control actions. The benefits of using graphical code LabVIEW over conventional high level language is the graphical user interface, which is built-in, intuitive in operation and simple to apply. The computer based software control offers more flexibility in modifying the control strategy [17].

E. Multimedia Features

The Microsoft (MS) NetMeeting is an Internet-based videoconferencing tool offers various features such as video, audio, whiteboard, file transfer and text chat. It is very user friendly, as the audio and video turns on automatically when a connection has been established between server and client. A one-to-one synchronous dialogue is very close to face-to-face interaction in a traditional classroom. The on-screen white board offers an interactive space with many functions that traditional boards in classrooms do not have. Apart from offering basic features such as pen, a highlighter, an eraser, it allows the user to display the information from any Windows-based application on to a white board. The white board provides an ideal platform for constructive teaching and learning. The another useful feature supported by NetMeeting is the file transfer function which is used to send additional course materials such as video, sound or text files for the future use by the receiving party. The only limitation of MS NetMeeting is that it is not suitable for subject delivery to a large group of learners [19].

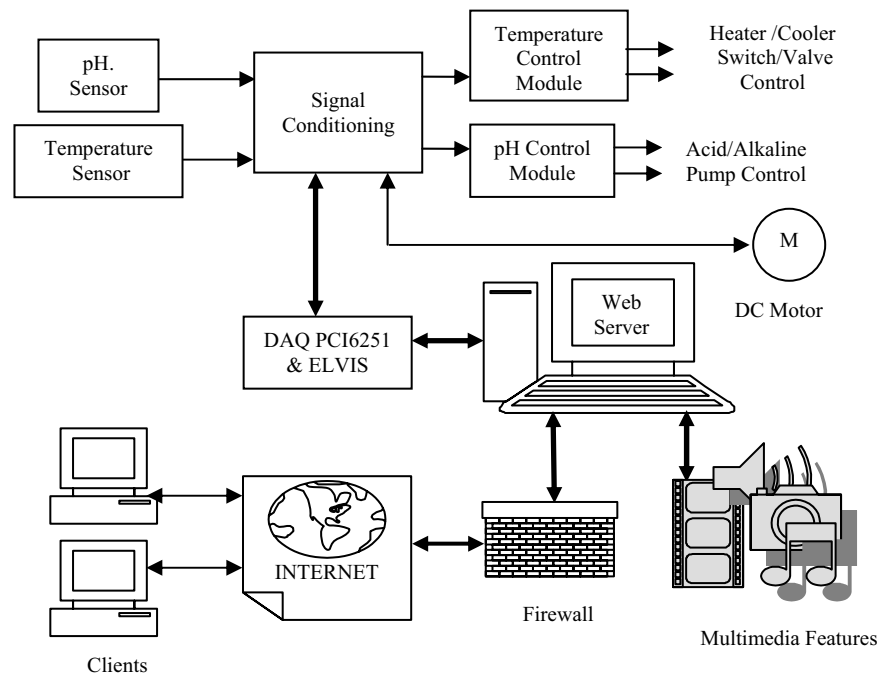


Fig. 1 System architecture for remote experiment on control of bioreactor process parameters

F. The Experiment

The concept is demonstrated by developing a web interface to control the bioreactor environmental parameters: temperature, pH and agitation speed using LabVIEW virtual instruments. NI hardware and the signal conditioning unit interface the different components of a bioreactor unit with the LabVIEW built-in web server. The VI control algorithms are developed to process the sensor inputs obtained through data acquisition system and generate the control actions based on the user set value of the parameter. In case of temperature control, based on the difference between the set value and the process value, the control actuations are generated to switch ON/OFF the heater or CLOSE/OPEN the solenoid valve of the water cooling system using digital output ports of ELVIS. Similarly, for the pH control, the signal generated to control ACID/BASE pumps and correspondingly switch the LED indicators displayed on the front panel. The counter output line of the ELVIS is used to generate PWM (Pulse Width Modulation) signal with varied duty cycle to control the agitation speed of the process.

III. SOFTWARE STRUCTURE

The virtual instruments are developed to display the actual value of the process variables and control the process parameters using PID algorithm. The sensor electrical signals from the DAQ system are converted to read the actual value of temperature and pH using a simple multiplier with a suitable constant calculated by the operating range of input voltage. These values are compared with the user set values and the difference

produces the error value. This error is further processed by the LabVIEW PID control algorithm and produces the digital output to the actuators.

A. Real Time Control

The notion of real time control implies that the operation relies on absolute time and the process is irreversible with respect to time. The operations are generally performed in correspondence with the physical hardware. The hardware system state is made available to the server through appropriate interfaces such as DAQ system and the transducers. The data acquisition and processing operations are performed by acquiring finite number of samples and post processing them to generate the actuations to the control system [20]. The actuation values are computed and written to the output ports of DAQ system at every cycle. The actuators and amplifiers are interfaced with the output ports to enable the web server to drive the physical system with the required amount of energy. The block diagram shown in Fig. 2 describes the structure of the process control loop for bioreactors environment, where the process parameters temperature and pH are controlled. The difference between the process variable and the set point is called error, which is processed by the PID controller with suitably tuned coefficients to maintain the error close to zero.

B. PID Control Algorithm

The PID control system provides a generic and efficient solution to real world control problems by offering treatment for both transient and steady-state responses of the system.

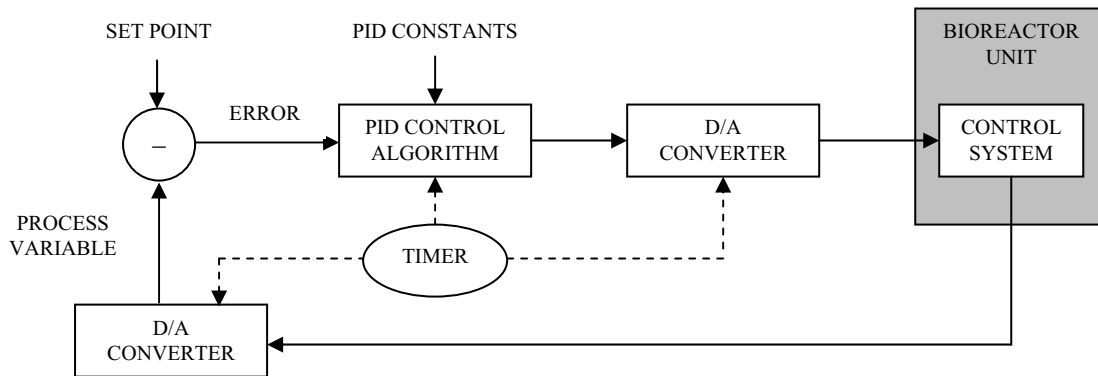


Fig. 2. Structure of the process control loop

The PID controller works in a closed loop system produces the signal output proportional to sum of Proportional, Integral and Derivative control actions. The proportional control action reduces the rise time and steady state error and provides an overall control response proportional to the error signal through the allpass gain factor. An integral action eliminates the steady state error through low-frequency compensation, but it makes the transient response worse. The derivative control action reduces the magnitude of the overshoot produced by the integral component and improves the combined process control stability by improving transient response through high-frequency compensation [18].

The PID control algorithm is used to control the temperature and the pH values of the bioreactors environment. The graphical PID controller program contains four subprograms: Proportional, Integral, Derivative and the program to compute real time difference between the successive samples. The mathematical expression for the PID controller output $V_o(t)$ is given by,

$$V_o(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \quad (1)$$

Where $e(t)$ is the error, K_p , K_i , K_d are coefficients of proportional, integral and derivative actions respectively.

The proportional control action is directly implemented in LabVIEW using a multiplier with a proportional constant. The integral action is evaluated by trapezoidal method and the corresponding mathematical representation for the successive samples with time difference T is given below.

$$\int_0^n e(t) = \sum_{k=0}^n \frac{[e(kT) + e(\{k+1\}T)]}{2} T \quad (2)$$

Where $k=0, 1, 2 \dots n$, and T = sampling time. Similarly the derivative action is evaluated using the backward difference method as follows.

$$\frac{de(t)}{dt} = \frac{e(kT) - e(\{k+1\}T)}{T} \quad (3)$$

The integral and derivative actions described in (2) and (3) respectively, are implemented using shift registers and a while loop function of LabVIEW with its conditional terminal is connected to Boolean false constant. This while loop and shift register combination reads each new error sample at very execution by shifting the successive samples, hence the functionalities of integral and derivative actions in real-time could be achieved. The successive samples are read in each iteration of the while loop and the control actions are updated continuously. The sampling rate is decided by the data acquisition system which can be configured in web server. The practical time difference between the successive samples is considered to evaluate the integral and derivative control action. The subprogram to compute real-time difference between the successive samples is also uses the while loop with a false constant and shift registers with an input derived from a tick count function. The tick count function of LabVIEW evaluates the time difference between the successive samples in milliseconds and is converted to seconds before using with integral and derivative functions. The control parameters are tuned such that the closed loop control system should meet the desired objectives associated with the stability, rise time, overshoot and robustness against the environmental uncertainty [13].

The Fig. 3 shows the graphical code to control the temperature of the bioreactor process. Similar techniques are used in the control of pH value of the process.

The algorithmic steps used in the development of VI block diagram are given below.

1. Select the physical channel corresponding to the signal input of DAQ device.
2. Set the sampling rate using the sample clock of the analog input. This allows the internal characteristics of the acquisition to be as efficient as possible.
3. The process variable (P_V) is passed to VI and the difference between P_V and set point (SP) produces the error signal $e(t)$.
4. Call Proportional control VI. This takes specified error value and gain to calculate the output.

5. Call Time difference (Δt) function VI. This calculates the time difference between the successive samples.
6. Call Integral and Derivative Control VI. This uses the inputs: error value, coefficients, time difference (Δt) and calculates the output value for the given process variable.
7. Add the output of P, I and D control blocks and verify the PID output is within the range between upper limit and lower limit controls. If YES, this value is passed out at *Coerced* terminal and a *true* Boolean value at *In Range* terminal of the *In Range and Coerce* function of LabVIEW. If NO, then the set value upper/lower limit passes out based on the PID output is larger/smaller than the upper/lower limit and *false* Boolean value at *In Range* terminal. The Boolean value is used to prevent the integral wind-up.
8. Select digital output channels and generate the signals to control the temperature of the process and operate the relays for pH control.

C. Control of Agitation Speed

The speed control of the DC motor is achieved by PWM technique by generating the pulses with duty cycles controlled by VI. The counter outputs of the DAQ system is used to generate the PWM signal by creating DAQmx virtual channel [16]. The complete range of motor RPM is converted to the duty cycle of the pulse ranging from 0.1 to 0.9 with a fixed frequency and used as input to the DAQmx virtual channel. The RPM of the motor is measured using non-contact proximity switch, which generates a pulse for the one rotation of the motor. By counting the number of pulses through digital input of ELVIS, the RPM is calculated.

D. Remotely Accessible Virtual Instruments

The LabVIEW programs are called Virtual Instruments because their appearance and easy operation imitate the real instruments. It includes extensive libraries of functions for many programming tasks, such as data acquisitions, data analysis, data presentation and storage. The front panel to control the process parameters of the bioreactors environment consists of a display unit, control unit and the indicators. The display unit includes thermometer, pH meter and the RPM meter to measure the agitation speed of the process. The control unit has the facility to input the desired operating values (temperature, pH and agitation speed) and PID coefficients. The indicators display the actions performed on the bioreactors process to achieve the required value set by the user.

E. Collaborative Learning

The collaborative and supported learning is embedded in a web browser and navigated using a tab system developed in HTML. Functionally it has three distinct but interconnected sections comprised of learning support resources, i.e., remote experimentation facilities, collaborative working and communication tools.

Collaborative learning environment provides opportunities to interact, practice and to understand the need of working [5]. The Information and Communication Tools (ICT) support collaborative activity and this experiment uses the tool MS NetMeeting. The MS NetMeeting along with LabVIEW VI provides an ideal platform for collaborative learning with on-line access of remote experiments. Fig. 4 shows the web page of the control panel and real-time video window of the bioreactor process.

IV. HARDWARE INTERFACE TO PROCESS CONTROL EXPERIMENT

The National Instruments NI ELVIS along with data acquisition card PCI6251 and custom designed signal conditioning circuits are used to interface the web server with the laboratory experiment. The data acquisition system PCI6251 and NI ELVIS workstation supports 6/12 channels of analog inputs in Differential/Referenced Single Ended mode, 2 channels of analog output and 8 digital I/O channels. The data acquisition system can be operated in analog mode up to signal level $\pm 10V$. The digital I/O's are TTL compatible with 8 bit resolution. The digital outputs are used to generate control actuations to temperature and pH control modules and analog inputs interface the sensor and measurement circuitry with VI. The temperature and pH sensor outputs are amplified and fed to the analog inputs of the ELVIS workstation and further processed by the graphical code of PID control algorithm and generates the output at the digital output ports of ELVIS. Table 1 describes the interface details of DAQ system with the experiment hardware.

The counter output of ELVIS is designed to generate PWM pulses to the 12V DC motor which controls the agitation process of the bioreactor. The signal from Non-contact proximity switch is interfaced with the digital input of ELVIS and further processed to produce RPM of the agitation speed. The design of web interface to bioreactor unit in an education application is to allow critical analysis and fast understanding of the process. On this context, a web-based interface designed is not exactly mimicking the conventional system, but simplified version of it.

TABLE I.
SERVER INTERFACE WITH EXPERIMENT

Sl. No.	Physical Component of the Experiment	ELVIS Interface
1	Temperature Sensor	Analog Input (AI0)
2	pH Sensor	Analog Input (AI1)
3	PWM output	Counter output (CTR0 – OUT)
4	Heater Switch Control	Digital Output (DO0)
4	Solenoid Valve Control (Water Cooling)	Digital Output (DO1)
5	Relays (ACID & Alkaline Pump Control)	Digital Outputs (DO2 & DO3)
6	Non-contact Proximity Switch (DC Motor Speed Measurement)	Digital Input (DI0)

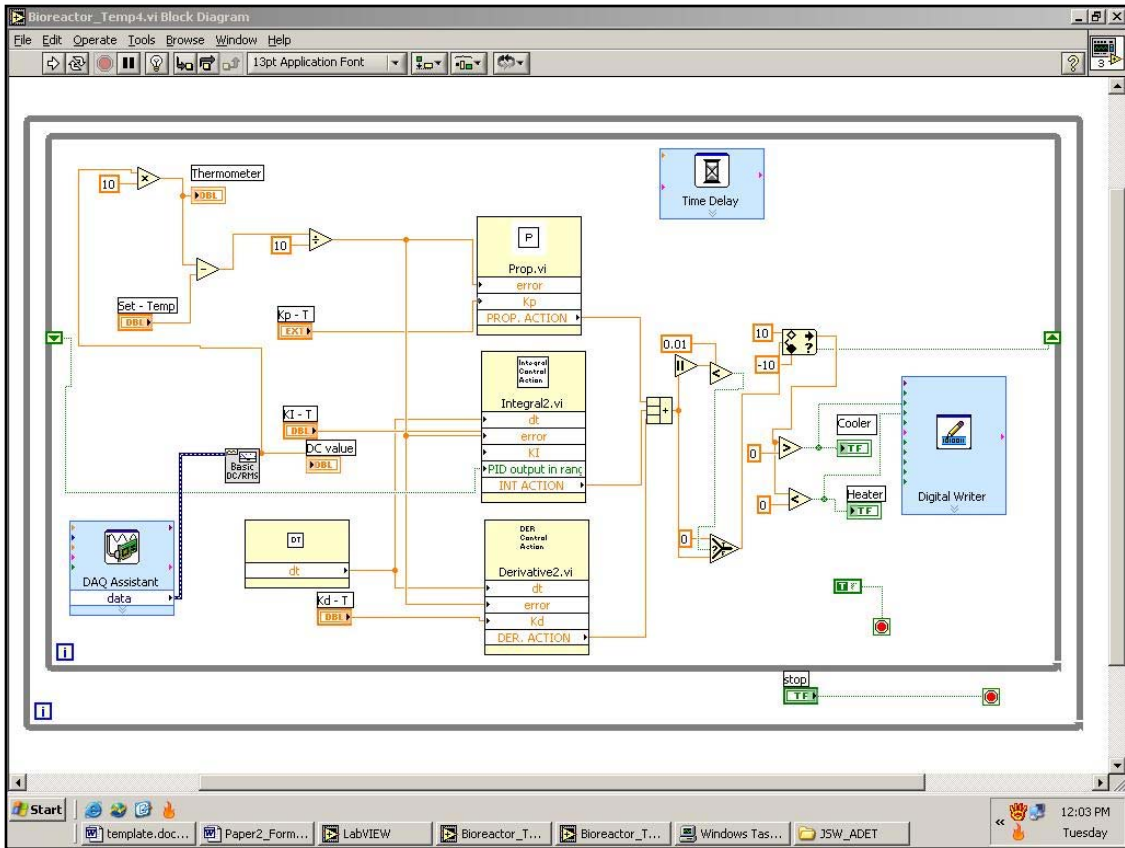


Fig. 3. VI Block diagram to control the temperature of the bioreactor process

The screenshot displays a web-based user interface for a bioreactor. The interface is divided into several sections: 'Display Unit' showing 'Thermometer' (27.8), 'pH meter' (6.5), and 'Agitation Speed' (291.9); 'Control Unit' with sliders for 'Set - Temp' (40), 'Set - pH' (8), and 'Set - RPM' (300); and 'Indicators (ON/OFF)' for 'Cooler', 'Heater', 'Relay 1 (Acid Pump)', and 'Relay 2 (Alkaline Pump)'. A video window shows the physical bioreactor setup. A 'white_board.NMW' window displays a LabVIEW block diagram for derivative control, showing the error signal being processed by a derivative block and then a gain block to produce the 'DER. ACTION' output.

Fig. 4. Web page of the user-interface along with video window and a white board containing VI code for derivative control

Besides technical limitations such as time delay caused by web information traffic, the other aspects such as security and coordination among multiple users are handled by web-server. The control loop is installed on server and the control actions are regenerated whenever the client updates the changes in control parameters on Web page. The old set of parameters remains active until a new set of parameters are received by the web server. Therefore, Internet delays do not affect system performance [12].

V. CONCLUSION

Internet promoted connectivity is unrivalled when it comes to on-line learning as it enables the collaboration between skilled workers situated in geographically diverse locations. The work presents the architecture for Internet based operation aiming primarily at educational applications. The developed system uses LabVIEW Virtual Instruments to generate control algorithms and control panel which can be accessed through the web. A web interface using graphical code and National Instruments data acquisition system benefits with user friendly access and control of process parameters of bioreactors environment. The multimedia features support collaborative control with visual display of the remote device. To minimize the internet attacks, server is equipped with remote identification and authorization, as well as firewall to keep away eventual attacks. Communication failure is another risk which is overcome by avoiding time critical operations of laboratory process.

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