WebLabs in Control Engineering
Education: status and trends

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Abstract: In 1995, Prof. Jim Henry built a WebLab (Henry, 1998) at the University of Tennessee at Chattanooga (UTC). Currently, the WebLab of UTC has had over 10,000 laboratory experiments per year conducted on shared equipment. The experiments have been on a variety of feedback control systems, motor-generator systems, heat exchange, combustion, distillation, kinematics of machines, forced vibrations, batch drying, journal bearing pressure distribution and others. The web address for the WebLab is http://chem.engr.utc.edu. Collaborating with UTC Prof. Herbert M. Schaedel and Prof. Serge Zacher translated web pages into German language and used the remote laboratory experiments for the education at the Universities of Applied Sciences Cologne, Wiesbaden and Darmstadt.

After using the UTC-WebLab for several years Prof. Zacher initiated a project to design and build similar WebLab stations at the University of Applied Sciences RheinMain (HS-RM), which is ready to be applied in 2010. This paper describes the actual technical stand of WebLabs and describes the data acquisition methods. The special attention is paid to the teaching methods of control engineering with both laboratories of UTC and HS-RM using online experiments.

Keywords: controls, engineering, education, internet, experiments

1. Introduction

Internet access and Web browsers are today available on nearly every PC or laptop in universities all over the world. The Home-PCs or laptops of students are mostly equipped with it. That was the reason why 1971 the NSF (National Science Foundation) began in the USA two big projects TICCIT (Time-shared Interactive Computer Controlled Information Television) and PLATO (Programmed Logic for Automated Teaching Operations). The goal of both projects was similar: to show how efficient is the online education via Internet.

Since the efficiency of the Web-based learning was successfully proved a new term elearning is used encompassing all forms of online learning. This term has different meanings to different people and different education branches. It is ambiguous also for those who are inside the elearning industry, but generally under elearning is understood an online learning platform or a virtual classroom.

Also with industrial companies, which often use the company network to deliver training courses to its employees and in most universities, the word elearning is used to define a specific mode to attend a course or program of study where the students rarely or never meet face-to-face, nor access on-campus laboratory devices and other educational facilities, because they study online.

The WebLabs described and discussed in this paper, are not virtual, but real laboratories with real devices, which can be used and activated by students via Internet with elearning platforms. The fact that WebLabs, used in this paper are not “virtual laboratories,” is often ignored by students and by professors, who are not familiar with the principles of remote controls.

Although the remote control is widely known for those outside the industry, the control of laboratory devices is understood as a simulation like MATLAB /Simulink and other software tools.

In the reality the concept of WebLab is the combination of remote control of labor equipment with the databank and with virtual tools for data transfer from campus to the user. Of course the simulation could be done by user himself, when the experimental results are transferred.

The best classification of elearning laboratories is done by www.e-teaching.de. According to this classification there are three kinds of laboratories:

1. Remote laboratories, where users (students) do experiments with real devices which are placed far from user.
(2) Virtualized laboratories, where instead of real devices students experiment with simulations.

(3) Partly virtualized laboratories, which are the same as HIL (hardware-in-the loop) or RP (Rapid Prototyping); that means the real devices are combined with simulations.

According to this classification the WebLabs of this paper are the same as remote laboratories. The emergence of technology enabling the establishment of computer networks has fostered the development of online laboratories.

Twenty-five years after first NSF projects, mentioned above, the international group of professors, including authors of this paper and directed by Prof. Henry, proposed NSF a new project called EVO-ELE (Engineering Virtual Organization for Engineering Laboratory Education). The goal of the project is to extend development of on-line laboratories, further the sharing of human and engineering resources, and encourage interactivity, cooperation and collaboration in distance-learning contexts.

2. Early WebLab Development

In 1995, Dr. Henry began connecting the experiments in his lab to the web to be operated remotely [Henry, 1998]. Prior to this, all the experimental stations in the engineering labs at the UTC were locally connected to computers for control, operation and data acquisition. Extending from there to the Web was conceptually straightforward. Subsequently, Dr. Henry’s team has built a data-base driven system that handles the queuing of the experiments and the collection, storing and presentation of the data.

Remote experimentation on the engineering laboratory equipment can be remotely operated, observed and data collected by students or instructors at a remote internet-connected location. The experiments can be run anytime, 24 hours a day, 7 days a week. Schools of all sizes and rankings can participate and accessing these on-line experiments and simulations. Instructors can use the on-line experiments in classroom or office demonstrations; students can use them in laboratory situations and for homework assignments. Application of these concepts and extension to international collaboration is described here. Student teams dispersed globally can work on the same experiments.

The stations used in control engineering education include air pressure control, motor speed control, generator voltage control, water flow control, level control, temperature control, distillation column control, drying oven control, gas-fired heater control, absorption column control and pressure-swing absorber control.

The air pressure control system consists of a 3-phase motor-driven blower fan forcing air into a system of ducts. The system has a variable-voltage, variable-frequency (VVVF) motor drive for the blower motor that is controlled by the data acquisition and control computer that is connected to the database server. A schematic diagram of the system is shown in Fig. 1. Eight other systems are described more completely, with diagrams, elsewhere (Henry & Knight, 2004).

![Fig. 1. Schematic diagram of control system for air pressure](image1)

Other universities have developed similar laboratories along the model developed at UTC. Fort Valley University in the U.S. has several stations. One of these is pictured in Fig. 2. Dr. Henry has shared demonstrations of these laboratories in the U.S. and abroad on many occasions. Fig. 3 is a photo of demonstrating the multiple-tank water level control experiment with other faculty at a conference.

![Fig. 2. A student at Fort Valley University working with an electric generator control system](image2)
Since 2006, Prof. Zacher has used the WebLab of Prof. Jim Henry, UTC, together with his own laboratories of automation, for his students at the Universities of Applied Sciences RheinMain and Darmstadt (Fig. 4-6). From seven stations for controls systems experiments, which all are inherently stable systems when run in open-loop configuration, he used mostly the single-input single-output systems of speed and voltage control.

Later on Prof. Zacher expended the use of the UTC-WebLab for students of CDHAW (Chinesisch-Deutsche Hochschule für Angewandte Wissenschaften) and for master-of-science students in Electrical Engineering of ZFH (Zentralstelle für Fernstudien an Fachhochschulen in Koblenz). All above mentioned students without exception were fascinated by the opportunities of the remote experiments and were very motivated. Most of them repeated the experiments many times from home PC’s for the evaluation of the test results and discussed them in their reports.

3. Broader Applications

Three of the laboratory systems have been used as models for hypothetical environmental system control applications.

The pressure control system models a paint spraying booth pressure control system to prevent fugitive paint and fume emissions. The motor speed control system models the drive motor on an aerator at a water treatment facility to properly control the oxygenation in an aerator. The water flow control system models a filter washing operation at a waste water treatment facility. The assignments to students are presented as important environmental applications of engineering control systems ( Slater, 2005).

4. International Collaboration

In addition to providing facility usage for the students at UTC, the usage of labs have been shared by students in Australia, Indonesia, Scotland, Canada, Germany and other countries as well as many U.S. universities. Labs such as these are considered laboratories of excellence for the digital age.

Collaborating with UTC for several years, and currently, Prof. Herbert M. Schaedel and Prof. Serge Zacher translated web pages into German language and used the remote laboratory experiments for the education at the Universities of Applied Sciences Koeln, Wiesbaden and Darmstadt. The results were partly published by [Henry & Schaedel, 2005], the description of methods and user manual are available online at [Zacher, 2009].

Fig. 3. Dr. Henry and 3 other faculty discussing and observing the operation a remotely controlled water-level experiment

Fig. 4. A Student of University of Applied Sciences RheinMain observing experimental response of the Chattanooga experiment

Fig. 5. Dr. Zacher introducing the UTC-WebLab to the students of University of Applied Sciences RheinMain

In using the WebLab, each student receives a personal task with the different operation points of the plant, different sizes of the input step and sends the configuration via Internet to the UTC. The step responses come back from UTC after 30-50 seconds as a text- and csv-file,
Repeating input steps for different operating points enables a static input-output diagram to be built with EXCEL as shown in Fig. 8. The steady-state operating curve will be linearized at the operating point and the gains will be defined. Very important for the use of the WebLab is the fact, that each student receives own operating point, so that the calculation results can not be exchanged between students and demands his or her own calculation.

Fig. 8. Static input-output diagram for the system (steady-state operating curve)

The transfer function can be developed and checked by a simulation. The unknown proportional plant with delay

\[ G_s(s) = \frac{K_{PS}}{(1 + sT_d)(1 + sT_2)...(1 + sT_n)} \]

will be approximated as the first-order plus dead-time model parameters for the dynamic system include system gain \( K_{PS} \), first-order time constant \( T_1 \) and the dead-time \( T_d \):

\[ G_s(s) \approx \frac{K_{PS}}{1 + sT_1} e^{-sT_d} \]

The dead-time term will be then replaced with a first-order delay block. The plant identification based upon UTC-experimental step responses is proposed for students as a standard exercise for adaptive control with solution (Fig. 9 below).

Fig. 9. Solution to the exercise 8.1 of the book [Zacher, 2010] for adaptive control, based upon UTC-experiments
Based upon defined transfer function of the plant, the parameters of the P- or PI-controller can be calculated. Controller tuning is done according to the method of optimum magnitude for optimal damping of 0.707 [Reuter & Zacher, 2008].

The controller tuning parameters will be sent to the UTC plant and the step will be given to the set point of the closed loop at the same operating point of the plant as before. The resulting response to the step-change in set point will be evaluated, and, if necessary, the controller parameters will be modified as shown in Fig. 10.

![Fig. 10. Simulation of the experimental results in MATLAB and the calculation of controller gain](image)

Another important feature of WebLabs to mention, namely, the supervising professor has access to the databank and can follow the activities of students in the all experimental steps. The databank allows the search by names, by numbers of the experiments files or by date. An extract from one laboratory report is shown below in Fig. 11. The final result can be compared with the MATLAB/Simulink simulation, as shown in Fig. 12.

![Fig. 11. Sample page from a student lab report.](image)

With the WebLab, it is easy to realize experiments, which are rather complicated to be used in the real time. As an example it is shown below, how the bode-plot will be defined.

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Input Value (%)</th>
<th>Output (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.100</td>
<td>29.021</td>
<td>84.076</td>
</tr>
<tr>
<td>1.114</td>
<td>29.809</td>
<td>92.603</td>
</tr>
<tr>
<td>1.128</td>
<td>29.986</td>
<td>109.241</td>
</tr>
<tr>
<td>1.143</td>
<td>29.491</td>
<td>101.750</td>
</tr>
<tr>
<td></td>
<td>......</td>
<td>......</td>
</tr>
<tr>
<td>1.555</td>
<td>22.748</td>
<td>101.088</td>
</tr>
<tr>
<td>1.570</td>
<td>25.410</td>
<td>95.600</td>
</tr>
<tr>
<td>1.586</td>
<td>27.646</td>
<td>82.866</td>
</tr>
<tr>
<td>1.600</td>
<td>29.021</td>
<td>81.973</td>
</tr>
</tbody>
</table>

Table 1. Results for Sine input
Frequency: \( \omega = 2\pi \cdot f = 12.56 \text{sec}^{-1} \)

Period: \( T = \frac{1}{f} = \frac{1}{2} = 0.5 \text{sec} \). From file \( T = 1.6 - 1.2 = 0.5 \text{sec} \)

Input: \( \dot{y} = 29.021 - 10 = 19.021 \) for example.
\( \dot{y} = 10 + 9.961 = 19.961 \)

Output: \( \dot{x} = \frac{237.799 - 81.973}{2} = \frac{155.826}{2} = 77.913 \)

Magnitude: \( |G| = \frac{\dot{x}}{\dot{y}} = \frac{77.913}{19.961} = 3.9 \)

Magnitude in dB: \( |G|_{dB} = 20 \cdot \log |G| = 20 \cdot \log 3.9 = 11.8213 \)

To obtain the results of 10 experiments with different frequencies in the real time one needs at least two hours. Using WebLab students get the same results in 10-15 minutes.

Evaluating these experiments students learn both: the methods how to define the phase with Lissajous-figures and how to plot the frequency responses, as it is shown in Fig. 13.

\( f = 2 \text{ Hz} \)

\[ |G(j\omega)| = \frac{K_{PS}}{\sqrt{1+(\omega T)^2}} \]

\( |G|_{dB} = 20 \cdot \log |G| \)

\( \varphi = -\arctan(\omega T) \)

\( f = 1 \text{ Hz} \)

\( f = 0.5 \text{ Hz} \)

Fig. 13. (a) Frequency responses
The best results could be achieved combining the remote experiments with the presented devices and comparing the experiments with theoretical expected values. For example, the web experiment with the UTC-motor was first discussed on the present motor (Fig. 14).

The open and closed loop were analyzed as follows:

Transfer function of the plant:
\[ G_p(s) = \frac{K_{PS}}{1 + sT_i} e^{-sT_f} \]

Approximation \( e^{-sT_f} \approx \frac{1}{1 + sT_f} \) \( \Rightarrow \)
\[ G_p(s) = \frac{K_{PS}}{(1 + sT_i)(1 + sT_f)} \]

Transfer function of the P-controller:
\[ G_R(s) = K_{PS} \]

Transfer function of the open loop:
\[ G_0(s) = G_R(s)G_p(s) = \frac{K_{PR}K_{PS}}{(1 + sT_i)(1 + sT_f)} \]

Tuning by optimum magnitude, type B:
\[ K_{PR} = \frac{(T_i + T_f)^2}{2K_{PS}T_iT_f} - \frac{1}{K_{PS}} \]
\[ K_{PR} = \frac{(3 + 5)^2}{2 \cdot 4.28 \cdot 3 \cdot 5} - \frac{1}{4.28} = 0.265 \]

Controller gain:
\[ K_{PR} = 0.27 \]

Transfer function of the closed-loop:
\[ G_w(s) = \frac{K_{PR}K_{PS}}{(1 + sT_i)(1 + sT_f) + K_{PR}K_{PS}} \]
\[ G_w(s) = \frac{1}{s^2 + \frac{T_iT_f}{1 + K_{PR}K_{PS}} + s\frac{T_i + T_f}{1 + K_{PR}K_{PS}} + 1} \]

Damping:
\[ \begin{align*}
\frac{1}{a_0} &= \frac{T_iT_f}{1 + K_{PR}K_{PS}} \\
\frac{2\vartheta}{a_0} &= \frac{T_i + T_f}{1 + K_{PR}K_{PS}} \\
\frac{1}{a_0} &= \frac{T_iT_f}{1 + K_{PR}K_{PS}} \\
\frac{2\vartheta}{a_0} &= \frac{(T_i + T_f)^2}{1 + K_{PR}K_{PS}} \\
\frac{1}{a_0} &= \frac{T_iT_f}{1 + K_{PR}K_{PS}} \\
\vartheta &= \frac{T_i + T_f}{2\sqrt{T_iT_f(1 + K_{PR}K_{PS})}}
\end{align*} \]
Expected damping:
\[ \beta = \frac{3 + 5}{2\sqrt{3 \cdot 5(1 + 0.27 \cdot 4.28)}} = 0.7 \]
Damping from experiment:
\[ \beta = 0.8 \]

Expected overshoot:
\[ u_{\text{MAX}} = 1.43\% \]
Overshoot from experiment:
\[ u_{\text{MAX}} = 0.5 \]

Retained error:

\[ e(x) = w - x(x) \]
\[ x(x) = \lim_{x \to \infty} G_w(x) \cdot w = \lim_{x \to \infty} K_{PR} \cdot K_{PS} \cdot w \]
\[ x(x) = \frac{K_{PR} \cdot K_{PS}}{1 + K_{PR} \cdot K_{PS}} \cdot w \]
\[ e(x) = w - x(x) = w - \frac{K_{PR} \cdot K_{PS}}{1 + K_{PR} \cdot K_{PS}} \cdot w = \frac{1}{1 + K_{PR} \cdot K_{PS}} \cdot w \]

Calculated retained error:
\[ e(x) = \frac{1}{1 + 0.27 \cdot 4.28} = 13.9 \]
Retained error from experiment:
\[ e(x) = w - x(x) = 30 - 5.4 = 24.6 \]

5. Developing a WebLab in HS-RM

After using the UTC-WebLab for several years Prof. Zacher proposed a project for students of the University of Applied Sciences RheinMain (HS-RM) with the task to design and build similar WebLab stations for a temperature plant. The project was supervised by Prof. Dr.-Ing. Gerd Küveler and Dipl.-Ing Axel Zuber and was finished 2009.

Three stations in three HS-RM projects have been completed:


The home page and legal disclosure page of the newly developed WebLab are shown in Fig. 15.
Fig. 18. Schematic arrangement of Database system

The hardware based upon PLC SIMATIC S7-300 of Siemens is shown in Fig. 19 - 22. For the data acquisition and transfer there is an original solution, combining Profibus and LabVIEW.

Fig. 19. Temperature plant with PLC Siemens

Fig. 20. Temperature plant with data-acquisition hardware
The Web pages in the HS-RM system include the following:

1. Start page
2. Login
3. Change password
4. Experiment choice
5. Temperature-control
6. Controller-Type (P-, PI-, PID-) shown in Fig. 23

7. Result (data)
8. Result (figures), an example shown in Fig. 24

9. Evaluation
10. Device description
11. Domain manager
12. Professor’s Domain
13. Student’s Domain
14. Profile actualisation, shown in Fig. 25

15. Help
16. LabVIEW information, shown in Fig. 26
6. Trends

Some professors from the US, Canada and Germany, collaborating with UTC for several years, and currently, developed a virtual organization called EVO-ELE (Engineering Virtual Organization for Engineering Laboratory Education), directed by Prof J. Henry.

The vision of EVO-ELE is that an engineering education is a world-wide collection of services between “experiment suppliers” (universities, instructors) and “customers” (students). In the area of new providers, there is enormous potential; as many as 100 of these could be added.

The other kind of member is a Customer. According to a data of UTC’s on-line experiments the number of users increased over 100,000 usages in the past 10 years. Though many of these are multiple uses by the same students, the data indicate easily 1000 or more high-interest customers. With this much usage, it is clear that other institutions and students can benefit from similar set-ups; therefore, EVO will offer seminars and workshops at national and international engineering education meetings to aid in recruiting a wide range of institutions dispersed around the world.

Initially, EVO-ELE has Suppliers in 5 different areas at UTC:
- engineering controls,
- electrical engineering
- chemical engineering
- mechanical engineering
- environmental engineering,

There will soon be at least 4 additional ones at the University of Florida (U.S.) in chemical engineering. In EVO-ELE we will recruit two other types of Suppliers to join EVO-ELE.

There are two types of new suppliers to this EVO:

(1) Existing remote lab providers who buy into our mission,

(2) New remote lab providers to whom we offer support and technology in exchange for adding their laboratory equipment and simulation to Web access.

EVO-ELE would be the funnel through which these services are organized and supplied. The EVO will work to have the assessment built into the system and integrated with the data base of usage.

The EVO has both research and learning goals. The research components of EVO-ELE are in two interconnected research areas: (1) how to best use the cyber-infrastructure to best provide remote operation for engineering equipment and (2) effective education.

Emphasis will be on aggregations of software components for on-line laboratories in order to enable their integration with other components. EVO will develop a series of Web and Grid service software component designs. The research work will focus on the ways of automating a lab environment design on the fly given that the following information and tools are provided and made available based on:

1) a pedagogical model including the content, the learning strategy, the media, and the delivery models;

2) some distributed user interfaces (including augmented and virtual reality elements) designed to be easily aggregated after retrieval from learning object reposito-
ries and hosted within the adequate local and remote web service reference frameworks.

The shared community resources will include engineering laboratory equipment, data, audio and video acquisition facilities, data archiving and data base retrieval services and, of course, web-based access.

The justification of EVO-ELE rests on two items:

1. The use of laboratories in engineering education
2. The ability to remotely conduct engineering laboratory experiments and complex interactive simulations.

The importance of Web Laboratories is supported by the Accreditation Board for Engineering and Technology (ABET). Students in laboratory experiences learn design of experiments, the importance of dynamic behavior, data analysis, creativity, communication, models, instrumentation, learning from failure, safety, teamwork, ethics, psychomotor skills, and sensory awareness. Dynamic behavior needs a special comment here: much of engineering education is steady-state analysis (even if steady oscillations); every actual laboratory experiment is a combination of transient and (hopefully) steady-state operation. The richness of behavior that can be observed in the transient operations is very broadening to students’ learning and, of course, the way much of life occurs. On-line laboratories can add to instructors’ menu of experiences to help students learn.

A recent European PROLEARN report stated that "Integration of on-line experiences in education is recognized by the research community as a very challenging development and deployment framework for advances in learning technologies and methodologies. As such, it is a key platform for driving and validating core research in Real-time Internet Communication, Interactive and Distributed Systems, Interoperability or Computer-Supported Collaborative Learning. The availability of online experiments is also recognized as a key factor for really enabling the future dissemination of technology-enhanced learning) in applied sciences, technology and engineering-oriented professional and academic domains.

"The educational stakeholders in those demanding domains are aware of the promises and the challenges related to online experiments and are trying, often starting from scratch and alone, to handle them. Online experiments are at an early stage of adoption as learning resources."

7. Concluding remarks

The use of remote experiments from UTC for obtaining plant data and designing feedback controllers was entirely successful by all cooperated professors of USA, Canada and Germany. The WebLab can be used in teaching as well as real laboratories or industrial applications.

An extension of the tool may be done quite easily by adding sheets and introducing hyperlinks.

The Engineering Virtual Organization for Engineering Laboratory Education (EVO-ELE) is called to continuously develop and extend the concept for educational purposes in order to illustrate modern methods of control engineering for application in industry. The EVO-ELE is directed by Prof. J. Henry from UTC and includes today 7 members from Washington State University, University of Illinois, University of Florida, University of Quebec and Prof. Zacher, represented Universities of Applied Sciences RheinMain and Darmstadt. The first example of the effective EVO interaction is the developed WebLab of HS-RM.

Learning how people learn, while also supporting the very best ideas in the world-wide engineering are essential goals in today’s changing world. The fully developed WebLabs in Controls Engineering Education will have an enormous impact on both education and society by expanding the availability of engineering education for students throughout the world whose access to equipment may be limited or non-existent.

Schools of all sizes and rankings can participate in supplying and accessing these on-line experiments and simulations. Instructors can use the on-line experiments in classroom or office demonstrations; students can use them in laboratory situations and for homework assignments. Student teams dispersed globally can work on the same experiments.

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