

Exploiting an Engineering *Building* as a Unique Distance-Learning Tool*

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At the University of Colorado at Boulder, the custom design and construction of a 34,500 square foot laboratory and classroom facility from the ground up provided a unique opportunity for engineering educators to use the building itself as an educational tool. This curricular concept and accompanying building data system at the ITL laboratory is called 'Building-as-a-Learning-Tool,' or BLT. The web-based BLT software system continuously monitors more than 300 building systems sensors, enabling engineering faculty and students to use the BLT system as a distance-learning tool to take the 'pulse' of the building from anywhere in the world (see <http://blt.colorado.edu>).

INTRODUCTION

WHEN THE INTEGRATED Teaching and Learning Laboratory (ITLL) was conceived, designed and built in the mid-1990s, engineering educators envisioned using the facility *itself* as a unique engineering learning tool. Recognizing that *any* building of this scale (34,500 square feet over three floors) requires a myriad of engineering systems to function, the facility was intentionally designed to serve as an educational tool for students at the College of Engineering and Applied Science at the University of Colorado at Boulder. This curricular concept was called 'Building-as-a-Learning-Tool,' or BLT. Today, the ITL laboratory is a bustling, state-of-the-art learning environment supporting 2,600 students in 11 undergraduate engineering programs in six departments. Dedicated in 1997, the ITL laboratory includes two first-year design studios, an active-learning arena, two large, open laboratory plazas, teamwork areas, and manufacturing and electronics fabrication facilities for students [1]. Its open architecture supports two fundamental design concepts: *visibility* and *flexibility* (Figs 1 and 2).

The objectives of the BLT concept are:

- to increase the awareness of engineering students about the pervasiveness of engineering systems in their environment;
- to monitor the 'pulse' of the building in real time and make the data universally available 24 hours a day;
- to allow student opportunities to manipulate selected building systems; and
- to educate the public at large about the role of engineering in today's buildings, supporting the

ambitious engineering outreach initiative of the ITL program [2].

Engineering faculty, instructors and students can use the BLT system as a distance-learning tool to take the 'pulse' of the building from anywhere in the world (see <http://blt.colorado.edu>).

BUILDING-AS-A-LEARNING-TOOL (BLT) COMPONENTS

Four basic elements comprise the BLT concept:

Exposure—The building itself presents an open architecture with, for example, exposed heating and ventilation ducts, and visible computer network pathways. Many mechanical systems are color-coded and showcased behind glass curtain walls. Transparent wall and ceiling 'slices' reveal a variety of engineering details that are usually hidden from public view [3, 4].

Measurement—During the construction phase, more than 300 sensors were incorporated into the building to continuously monitor its performance. The web-based remote-access data measurement, acquisition and manipulation system for these sensors is the focus of this paper.

Manipulation—The two first-year design studios are essentially identical adjacent spaces, but with different climate control systems. One room features direct digital controls and is isolated from the rest of the ITLL's climate control system, allowing students to manipulate the system (within reason!) and measure the effect. A mechanical VAV box with a Plexiglas view panel reveals its inner workings. A separate experimental computer network is planned to allow students to experiment with an *in situ* network without jeopardizing laboratory

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Fig. 1. The Integrated Teaching and Learning Laboratory.

operations. However, this network has not yet been implemented.

Documentation—An extensive resource of digital and hard-copy drawings and other documentation describing the construction and process is available for review by faculty and students. The construction site was photographed with a permanently mounted video camera, with the image posted to a website and updated every 15 minutes. After construction was completed, these images were combined into a brief time-lapse video showing the entire construction process in a few seconds. In addition, video clips were taken of many phases of the construction process and recorded onto a searchable CD-ROM library.



Fig. 2. An open laboratory plaza inside the ITL laboratory.

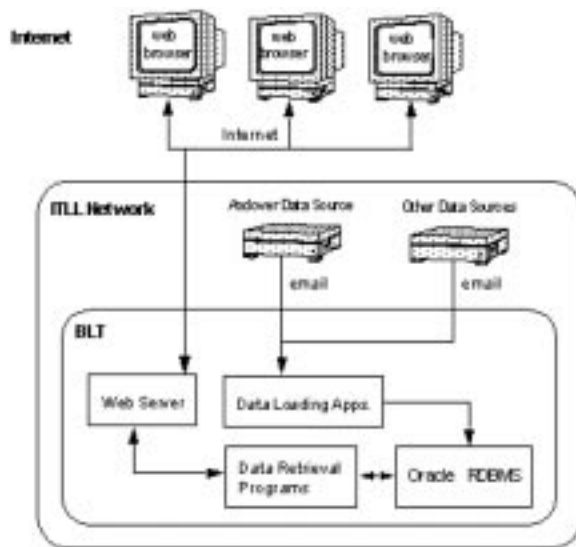


Fig. 3. Data flow diagram of the BLT system architecture.

SYSTEM ARCHITECTURE AND INVESTMENT

Figure 3 displays a data-flow diagram of the BLT system architecture. It is comprised of both a primary and a secondary data acquisition system and a web-based data retrieval system. The primary data acquisition system consists of a set of independent data acquisition devices, each of which collects data from one or more groups of sensors. These data are sent to the secondary data acquisition system, where they are centrally maintained and made available for web-based retrieval.

Costs of creating the BLT sensor and application software system were in addition to the expense of constructing an arguably more expensive building that was designed to expose and showcase a myriad of engineering systems for illustrative purposes. The increased construction cost for BLT sensor installation was approxi-

Table 1. Description of the BLT sensors and sample educational applications

Group (Quantity)	Sensor Group Description	
	Example Sensors	Sample Educational Applications
HVAC (129)	Measurement of building system and environmental parameters. Facilities Management uses sensors for building monitoring and control. Data allow students to investigate the state of the building in real time and study how a commercial building operates, with access to actual data sets. Exhaust airflow Building ventilation fan status Heating steam pressure Return fan total energy usage Building static pressure set-point	<ul style="list-style-type: none"> • Study thermodynamic processes for building heating and cooling • Estimate total building energy usage • Calibrate models of equipment performance
Building Environment (70)	Temperature sensors located throughout the ITLL building. Data used for the demonstration of engineering principles such as heat transfer in the cross-section of the building walls, thermal stratification through the vertical height of the building, or thermal performance of window glazing systems. A unique benefit of sensors installed within walls and foundations during the building construction is the ability to measure temperatures at locations that would normally be inaccessible. Foundation wall temperature Window glazing temperature Building air stratification temperature	<ul style="list-style-type: none"> • Calculate heat transfer in concrete building walls • Measure temperature stratification in vertical building air spaces
Roof Weather Station (11)	Measurement of meteorological properties from a rooftop station on the ITLL laboratory. Air temperature Barometric pressure Relative humidity Carbon monoxide concentration Incident radiation Wind speed and direction	<ul style="list-style-type: none"> • Correlate atmospheric carbon monoxide levels with local weather conditions • Measure and analyze long-term weather trends
Ground Weather Station (44)	Measurement of local weather and hydrologic conditions at, near and below the ground surface, with special emphasis on theoretical and applied hydrology. Allows a student to collect long-term data not typically measured by standard weather stations. Ground radiation energy flux Accumulated precipitation Wind speed	<ul style="list-style-type: none"> • Calculate net energy fluxes from soil • Measure variation of wind speed with distance above the ground
Building Structure (64)	32 strain gauges and 32 associated thermistors attached to structural columns and to an exposed and highly visible structural steel truss in the main ITLL lab plaza. The orientation of the cross-sections of the truss makes it possible to place the strain gauges at different angles to the longitudinal axis and measure different strain components due to bending of the truss. Strain on an engineering truss Truss temperatures	<ul style="list-style-type: none"> • Demonstration of engineering strain through the application of loads to a structural truss • Measurement of the effect of external loads (such as snow on the roof) on the resultant load on the truss

mately \$50K. The system took advantage of the Andover building control system, which was installed to control the building's interior environment. BLT web server hardware cost an additional \$19K. Most significantly, the personnel cost to develop and implement the web-based, searchable data collection and analysis application has been approximately \$195K. Ongoing BLT system maintenance costs for the 24 × 7 system average \$10K yearly, including upgrades of system software underlying the application (Oracle database software, etc.).

SENSOR BASE AND DATA SOURCES

The BLT system compiles data from more than 300 sensors distributed throughout the Integrated Teaching and Learning Laboratory. Sensors are categorized in five groups (see Table 1).

Computed values and set points

In addition to sensors, many computed or input values appear as data in the BLT system. *Computed values* are derived or calculated from other measured values. Examples of computed values include total energy usage, total mass flow through the cooling system, instantaneous power usage by building air circulation fans, total accumulated precipitation, and average wind speed. *Input values* are static values used as set-points by the HVAC system. Examples include domestic hot water temperature, building static pressure, and building air temperature.

DATA ACQUISITION SYSTEM

Primary data acquisition system

The primary data acquisition system consists of three independent sub systems:

- The *HVAC, Building Environment* and *Roof Weather Station* sensors are connected to an Andover CX9200 general-purpose building control system. Generic industrial sensors include relays, pressure transducers, thermistors, and air flow meters. The system can be configured for different sampling rates and to perform computational operations on incoming data. The central control panel is connected to an Ethernet network and has a designated IP address. A computer accesses the Andover data acquisition system via the Ethernet. In this manner, the computer downloads the data from the central control panel at regular intervals (typically, every five minutes). Once collected, data are e-mailed to the secondary data acquisition system.
- A *Ground Weather Station* is installed near the ITL laboratory. A weatherproof box houses a Campbell Scientific CR10X data logger that samples the sensor data at five-minute intervals

and performs basic mathematical manipulation of the data, such as averaging or summation. The data logger is connected to a computer that e-mails the data to the secondary data acquisition system.

- The *Building Structure* sensors consist of strain gauges attached to structural steel in the main ITL lab plaza. Data are collected and processed through a Campbell Scientific CR10X data logger, as for the Ground Weather Station.

Secondary data acquisition system

The secondary data acquisition system runs on Sun Solaris (UNIX) and an Oracle relational database. All data submitted to the secondary data acquisition system arrive via e-mail. This approach yields several advantages:

- The primary and secondary data acquisition systems are physically independent. Hence, primary data acquisition is geographically unconstrained (i.e., data can be collected anywhere in the world and e-mailed to the secondary acquisition system).
- Data exchange via e-mail allows for asynchronous processing. For instance, when the secondary acquisition system is down for maintenance, e-mailed data backs up on the system's e-mail server and is delivered and processed when the secondary system restarts.
- Reliance on e-mail-based data exchange implies that all data communication logistics (timing, delivery, queuing, etc.) are handled by commercial e-mail server software. This released the system development team from developing this otherwise complex component.

One disadvantage of the e-mail-based approach is that it limits real-time applications, such as control. The time required constructing, sending, receiving and processing e-mail degrades any process that would use that information to control the system in real time. However, no such system-control curricular activities have been planned or encountered as yet.

When e-mail arrives at the secondary data acquisition system, it is first examined to see if a registered sender at a registered location sent it. E-mail that does not pass both tests is ignored. Legitimate e-mail proceeds to a data loading application that reads the contents and inserts the associated data in a central relational database. All data are stored in SI units and time-stamped using a 4-byte date/time representing the number of seconds since midnight, 1 January 1998.

Periodically, various programs run to check the state and integrity of the data acquisition system. For instance, all registered data sources have an associated 'grace period' within which they are expected to submit their data. When the grace period expires, e-mails automatically inform the various system administrators that

data from a registered source are no longer being received.

- Data can be requested as a plot (see Fig. 4) or as a list (see Fig. 5).

DATA RETRIEVAL SYSTEM

BLT data can be retrieved through a web-based data retrieval system (<http://blt.colorado.edu>). The retrieval system uses the Common Gateway Interface (CGI) protocol [5] for web-based applications and was implemented in C/C++ and Embedded SQL. The system is implemented on Sun Solaris running the public domain Apache web server. Data can be retrieved in two ways:

- Standard 'snapshots' retrieve data for pre-determined groups of sensors and intervals. For instance, the 'glazing' snapshots retrieve temperature data from selected windowpanes for the most recent 24 hours. Similarly, the 'weather' snapshot collects the most recent 60 minutes of data from a roof-mounted weather station.
- Arbitrary queries are issued through various online forms offering the complete list of sensors and facilities to interactively specify a time interval. Although a query may contain any combination of sensors, only a single time interval may be specified.
- Information on each sensor is available online, including the manufacturer's data sheet.

DATA AGGREGATION

Although data are collected using a specific sample period, many data applications require a larger sample period. For instance, although data may be collected once per minute, a particular exercise involving a sensor's data may require hourly averages. Although it is possible to perform the data aggregation after the base data have been retrieved from the BLT system, retrieving the base data first may well exceed the maximum size of a data request (currently set at 9000, approximately 31 days of a single five-minute sensor). Rather than submitting several requests for smaller data sets, users may specify a specific data aggregation as part of the data retrieval request. Currently available aggregations are 10- and 30-minute, one-hour, 12-hour, and one- and five-day minimum, maximum or average values. As the maximum request size applies only to the number of data points retrieved, rather than the number of based data points, this greatly increases the span of data retrievable through a single request.

CUSTODY AND EVENTS

The sensor base must be carefully maintained and periodically calibrated. Since neither BLT's primary nor secondary data acquisition systems

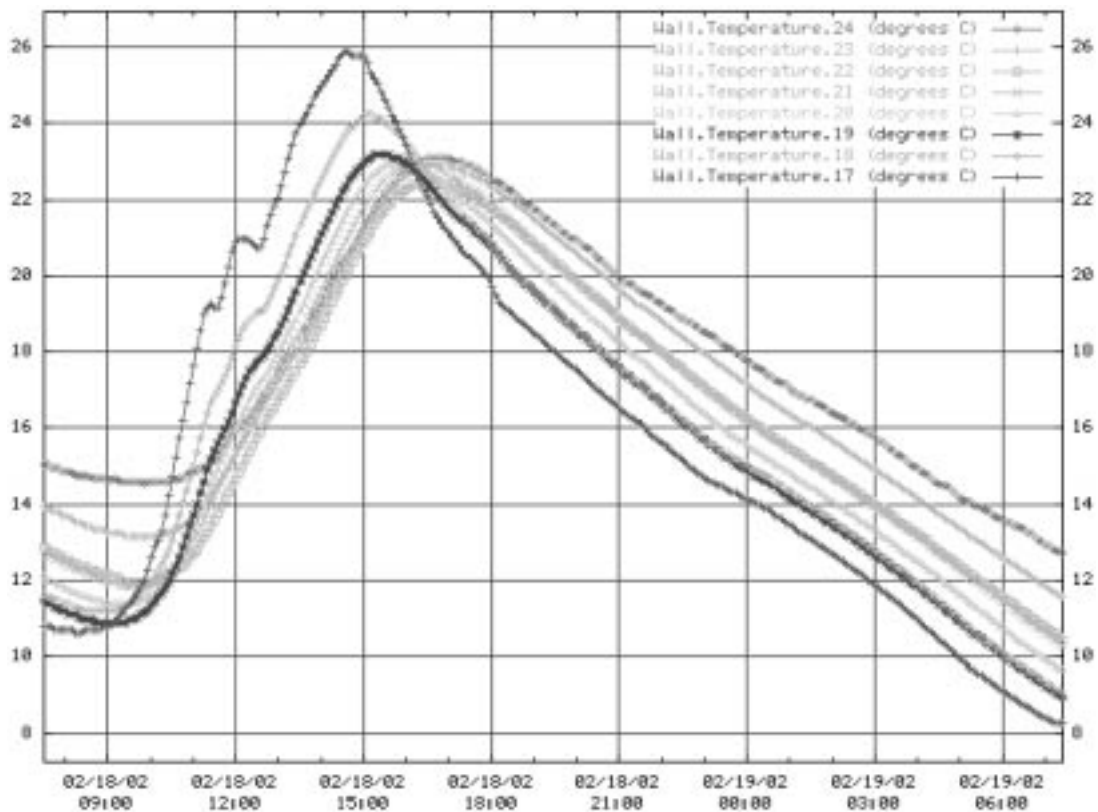


Fig. 4. Example data plot for 24 hours of wall-temperature data.

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BLT : Tue Feb 19 07:33:31 2002

LEGEND
S0-> #5 Wall.Temperature.5 (degrees C)
S1-> #4 Wall.Temperature.4 (degrees C)
S2-> #3 Wall.Temperature.3 (degrees C)
S3-> #2 Wall.Temperature.2 (degrees C)
S4-> #1 Wall.Temperature.1 (degrees C)

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DATE TIME	S0	S1	S2	S3	S4
02/19/2002 06:30	8.6389	7.7839	7.5389	6.4378	5.6811
02/19/2002 06:35	8.6389	7.7444	7.5061	6.4278	5.6111
02/19/2002 06:40	8.5589	7.6822	7.4389	6.3594	5.6061
02/19/2002 06:45	8.5389	7.6389	7.4228	6.3278	5.5111

Fig. 5. Example wall-temperature text data.

contain automated quality assurance/quality control mechanisms, data from sensors are stored indiscriminately. To mitigate this problem, the system offers two administrative facilities.

- Sensors may be put under 'custody' (i.e., the visibility of both a sensor and its data can be controlled). Three custody degrees are supported:
 - *Public*: Both the sensor and its data can be seen and accessed through the web.
 - *Protected*: Although the sensor can be seen through the web, its data can only be seen by the sensor's 'owner.'
 - *Private*: Only the sensor's owner can access the sensor and its data.
- Using this mechanism, system administrators may periodically take sensors offline, while retaining full access themselves.
- System administrators may submit so-called *events* to the BLT system. An event is defined as an arbitrary message associated with a time interval. The message can contain any text, but typically refers to special events or circumstances that (may) affect sensor readings. Examples are experiments conducted on parts of the building by students and/or instructors, special exhibits, building maintenance activities, sensor calibration activities, etc. Each data retrieval request is cross-referenced with the list of events. If the time interval of the data request overlaps one or more events, a highly visible hyperlink displays with the sensor data. Clicking on that link provides information about the event.

SEARCH CAPABILITY

Although it is straightforward to retrieve sensor data from the BLT system, it may not be as easy to find useful data in the very large archive of data that is maintained (July 1998 to the present). Depending on the requirements of the student assignment, data might have to conform to a certain pattern (e.g., wall temperatures for a cold/warm day or windowpane temperatures for a

two-week period with minimum temperature fluctuations). A search engine in the BLT system supports limited search capability based on the following criteria:

- begin and end time;
- sensor ID;
- relational operators (equal, less than, less than or equal, greater than, greater than or equal);
- specific data value; and
- logical operators (AND, OR).

Examples of searches supported by combinations of these criteria include:

'Search the period 1 January 2000 to 31 December 2001 for sensors X, Y and Z for data values larger than 20.0 and smaller than 30.0.'

'Search the period 1 January 2000 to 31 December 2001 for sensors X, Y and Z for sensor X data values larger than 20.0 and for sensors Y and Z data values smaller than 30.0.'

EDUCATIONAL APPLICATIONS

Engineering faculty use the BLT system as a distance-learning tool, asking students to use its capabilities to fulfill course assignments. Opportunities abound for engineering education coursework, assignments and curricular activities that use the BLT system (see Table 1). The use of the system in several mechanical and architectural engineering courses is described below.

Sample course applications

Mechanical Engineering Measurements Laboratory is a required junior-level course focused on measurements fundamentals and technical communication. Each semester, 40 to 60 students are enrolled. Experiments are drawn from a wide range of disciplinary topics. A BLT experiment designed for this course compares temperature measurements within a wall to a simple finite-difference, one-dimensional, transient, conductive heat transfer model [6]. It uses four sets of thermistors embedded through the walls of a light

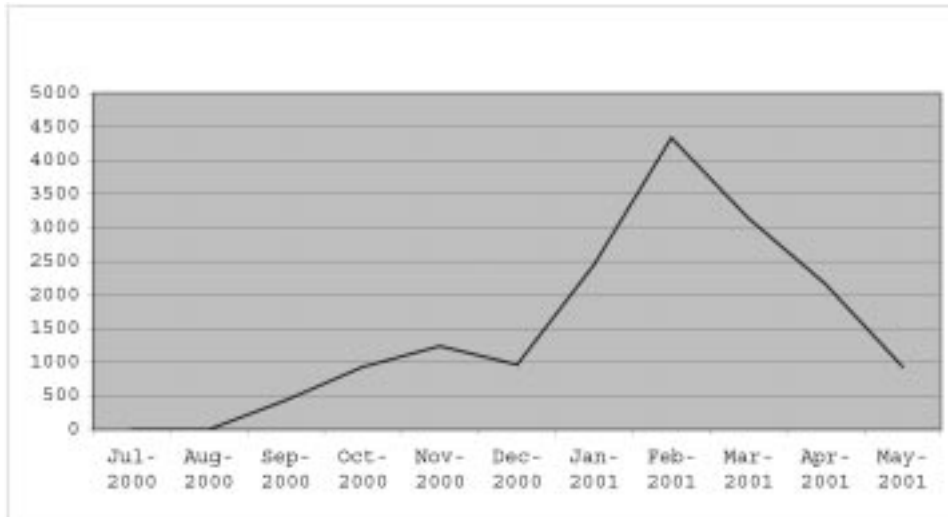


Fig. 6. Distribution of BLT website requests (by month, excluding developers and errors).

monitor in the roof (see <http://blt.colorado.edu/sensors> menu, sensors 1–32). Data at an arbitrary start time are used as initial conditions for the model, which is implemented in MS Excel (see <http://www.Colorado.EDU/MCEN/Measlab/Twoweeklabs/Procedures/timedepsoln.xls>). Data from the sensors closest to the inner and outer surfaces are used as boundary conditions. Assignment questions guide students through the analysis of the model-experiment comparison. A number of issues can be addressed, such as sensitivity of the model to parameters, effect of uncertainty in the thermistor measurements, and model accuracy as a function of time.

BLT data on the operation of the ITLL mechanical system are also used to complement several courses in the architectural engineering curriculum, including Mechanical Systems in Buildings, Building Energy Laboratory and HVAC Design. Data from the many mechanical components are used to reinforce and calibrate engineering models of equipment performance. For example, measurements of fluid temperatures and flow rates are used to calculate heat transfer rates in heat exchangers. The data allow calculation of the overall heat-transfer coefficient, UA , of the heat exchanger, which can subsequently be compared with the value calculated by heat transfer theory. The large amounts of data under varying operating conditions also allow examination of common assumptions in simplified heat exchanger modeling. While it is common to assume a constant value of the heat exchanger, UA , the data reveal the variation in UA with fluid flow rates and the magnitude of the variations under typical operating conditions.

The data from the BLT system are also valuable to understand the application of psychrometric processes to meet building heating and cooling requirements. The building is cooled by a single central air-handling unit (AHU) that uses an indirect-direct evaporative cooling system. At

various times during a given day, or throughout the year, the building may be conditioned by direct introduction of cooler outdoor air, direct evaporation of water into the ventilation air, or by chilled water circulating through a plate-fin heat exchanger. By examining the data, students can infer which system components are operational, view the impact of operation on system temperatures and humidities, and learn some of the strategies employed for energy-efficient space conditioning.

BLT USE ASSESSMENT

To evaluate BLT system use, server logs for the period 17 July 2000 to 11 May 2001 were analyzed. This period spans a full academic year during which a number of BLT-based exercises and homework assignments were given to CU undergraduate engineering students in a variety of courses. Figure 6 shows the resultant BLT website access frequency by month. Total number of requests for the period of record is 16,608, with a sharp increase during January–March 2001, when several instruc-

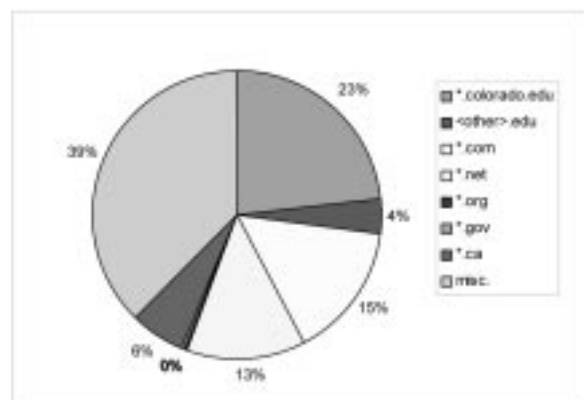


Fig. 7. Relative amounts of BLT sensor data requests, sorted by Internet domain origin.

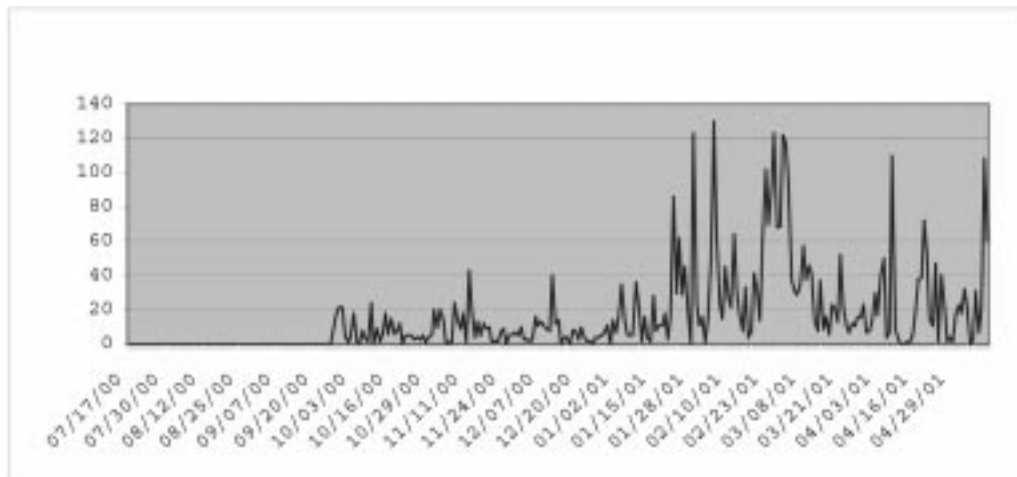


Fig. 8. Distribution of sensor data requests (daily data), reflecting engineering student data access.

tors directed their students to the BLT system website.

Figure 6 represents *all* requests submitted to the BLT system website (i.e., requests for sensor data as well as requests for other information). Since the BLT site offers extensive information on the nature of the ITLL facility and its various engineering subsystems, the sensors and the various quantities measured by the sensors, a large proportion of the requests logged by the server do not involve any sensor data. Requests for sensor data only during this period totaled 4,720, or 28% of the total number of requests. Sensor requests followed a similar distribution to that shown in Fig. 6.

Figure 7 displays the relative amounts of all BLT sensor data requests from this period, sorted by Internet domain origin. Most requests for sensor data originate from miscellaneous domains. However, the colorado.edu domain ranks second, with 23% of all requests for sensor data. Interestingly, '.edu' domains other than Colorado account for only 4% of all data requests. This points out the need to publicize the existence of the BLT system so that it can be integrated into engineering curricula elsewhere. Merely making data available on the web is unlikely to result in such integration.

Although Fig. 7 shows that the colorado.edu domain is a significant source of data requests (39%), it does not indicate whether or not the BLT system is used as part of the undergraduate engineering curriculum. To establish that relationship, it is necessary to analyze the timing of such curricular activities and the observed frequencies in data requests. Further analysis of the sensor data requests shows that the peak during the time period seems to be exclusively caused by requests originating from the colorado.edu domain.

Students were given assignments for the heat conduction exercise in Mechanical Engineering Measurements Laboratory, described earlier, on the following dates: 2/28/01, 3/7/01, 3/14/01, 3/21/01 and 4/18/01. Assignments were due two weeks

after these dates. Figure 8 shows the distribution of sensor data requests for this period. As could be expected on the basis of the monthly data shown previously, the record shows a marked increase in data requests during this time period. More interesting, however, is the pattern of spikes indicating short periods of sharply increased activity. Visual inspection of the timing of the spikes shows that a significant number occur during the various two-week time-frames during which students worked on their assignments. Furthermore, a t-test for the difference in the average daily frequencies of the periods showed a statistically significant correlation with due dates at the $p < 0.01$ level. These results would be even stronger if the activity peaks in January and February could be attributed to similar exercises from other courses. Although some instructors indicated that these peaks could well be the result of their student's work involving BLT, precise dated evidence is lacking.

ADVANTAGES AND LESSONS LEARNED

The unique BLT system offers a number of advantages over traditional laboratory experiments to both students and faculty. Data collection from heat-transfer experiments is typically time-consuming and tedious; BLT neatly avoids that drawback. Although the experiment is not 'hands-on,' the walls are easily visible to students in the ITLL, and the data reflect personal experiences of weather and diurnal cycles (e.g., it really is coldest just before dawn). However, this is perhaps more effective for local students. Another aspect that makes this a particularly effective lab experience is the good match between a simple model and a realistic experiment: the model can be run for eight hours before the accumulated error reaches 10%. Students also gain experience manipulating large data sets.

From a student's perspective, a distinct advantage of BLT-based assignments is that the data are

always available, allowing flexible time-management strategies. From an instructor's perspective, new data sets can be assigned to avoid recycled reports, as the data varies with the weather. Furthermore, any number of students can access the data during the period of an assignment, providing a similar but unique experience for each student in the class. BLT also provides a back-up lab experience in case of the failure of other laboratory equipment. Finally, the system is robust. Thus, BLT serves as a complement to hands-on experiments.

Given that many students access the BLT system independent of instructor supervision, it is important to provide supplemental material on the systems. In addition to the data, the BLT website provides information on the instrumentation, design specifications on the mechanical equipment, as well as descriptions of the overall interactions among the components in the mechanical systems. In fact, faculty did not consider the system fully useful until detailed sensor descriptions and specifications, including manufacturers' data sheets, were made available on-line in mid-2001.

One disadvantage of comprehensive instrumentation and monitoring is the opportunity for inconsistencies in the data. While conservation of mass and energy are two of the most fundamental engineering principles, it is common to observe apparent violations of these laws due to measurement errors. For example, it is difficult to accurately measure airflow rate and spatial average air

temperatures leaving the large chilled water coil when the coil has an area of $2\text{ m} \times 4\text{ m}$ and the air velocities can be as low as 1 m/sec. While analysis of measurement errors is an important element of engineering education, the lack of closure in energy balances across heat exchangers can create frustration for students in lower-level theory classes and distract from the intended assignment lessons. It is often helpful to limit the amount of data as a tactic to protect students from having to deal with such inconsistencies.

CONCLUSIONS

The measurement aspect of the web-based BLT software system, with 300+ sensors and hardware, enables engineering faculty and students to use the BLT system as a distance-learning tool and take the 'pulse' of the building from anywhere in the world. This provides educational opportunities for both local and distance students to work with large sets of actual real-time experimental data without having to collect it themselves, which can be tedious and time-consuming. However, making such data accessible on the Internet is insufficient to promote wide-scale integration into engineering curricula at distant institutions. Wide-scale publicity about the existence of the unique BLT system is necessary, as is the development and dissemination of curricular modules based on the system.

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