This paper describes the Integrated Teaching and Learning Laboratory (ITLL) of the College of Engineering and Applied Science at the University of Colorado (CU), Boulder. Not only does the building support and drive our curriculum but the design of the building was curriculum driven. In fact, the building itself serves as a laboratory instrument with more than 300 sensors embedded throughout the building and the opportunity to perform experiments on the building itself. All the sensor data are available on the Web. The ITLL is truly an example of Winston Churchill’s quote—"first we shape our buildings and then our buildings shape us.”

Keywords—Building management systems, building systems, buildings, education, sensors, technology-enhanced learning.

I. INTRODUCTION

The College of Engineering and Applied Science at the University of Colorado (CU), Boulder, has recently built a new laboratory facility designed to enable hands-on, team-oriented learning across all of its six departments. The three-story, 34 400-ft$^2$ Integrated Teaching and Learning Laboratory (ITLL) opened its doors in January 1997 with full-scale operation in August 1997. Its curriculum-driven design accommodates a variety of learning styles and features two first-year design studios, an active-learning classroom, a computer simulation laboratory, a computer network integrating all the experimental equipment throughout two large, open laboratory plazas, capstone design studios, group work areas, an electronics and instrument shop, and a student-accessible manufacturing center boasting two computer numerically controlled (CNC) milling machines, a CNC lathe, a laser cutter, a stereo lithographic three-dimensional (3-D) printer, and numerous other machines.

Designing this facility from the ground up has given us a unique opportunity to use the building itself as an interactive teaching tool to give students, as well as the public at large, an appreciation of the variety of engineering concepts and systems implicit in any modern building. Included in the “building-as-learning-tool” (BLT) concept of the laboratory is the capability to expose, monitor, and manipulate the facility’s many complex engineering systems.

In this paper we will review the pedagogical background of the ITL initiative, some of the curriculum changes which have been developed, and then concentrate on the use of the building itself as a living laboratory.

A. The ITLL

The ITLL, a 34 400-ft$^2$ hands-on learning facility that opened in January 1997, is the visible manifestation of a significant shift away from lecture based engineering education. The ITLL supports our new hands-on engineering curriculum in innovative and creative ways. CU has also become more involved in expanding engineering education to reach into the critical elementary through high school years.

The unique design and architecture of the ITLL facility was driven entirely by curricular reform objectives. It provides K–16 students with an interdisciplinary learning arena. K–12 learners experience the joys of learning in summer workshops. The principles of design are introduced during a student’s first year in engineering. Theoretical engineering science courses in the middle two years are augmented with hands-on, open-ended discovery opportunities. Finally, interdisciplinary teams of seniors design, build, and test real-world products.
II. INTEGRATED TEACHING AND LEARNING

The vision statement articulated by a team of faculty and students in 1992 continues to drive college-wide curriculum reform: *To pioneer a multidisciplinary learning environment that integrates engineering theory with practice and promotes creative, team-oriented problem solving skills.* The ITL curriculum integrates hands-on learning across all six engineering departments and throughout all four years of undergraduate study, beginning with first-year engineering projects. This college-wide course introduces students to the excitement of engineering and to the practical considerations of the design process including experimental testing and analysis, oral and written communication, multidisciplinary teamwork, and project management. Two dedicated design studios in the ITLL, shown in Fig. 1, provide the capacity to teach this course to all first-year students. The major component of this course is a design project through which students experience the complete design-build-test cycle that attracts many students to engineering in the first place. The design project is especially rewarding and more challenging when the student teams are meeting the needs of real customers from outside the university.

Past client-based assistive technology projects include a page turner for an adult with cerebral palsy, a talking backpack that answers “yes” or “no” at the push of a button by a mute child, and an assistive glove that allowed a quadriplegic classmate to grasp a can of soda. Another client-based design project theme is interactive learning exhibits: CU students learn while designing and building projects that help younger children learn basic concepts of engineering or science, either formally in a middle school class or informally in a museum setting. Examples include a system of levers and pulleys for a middle school class studying simple machines and a children’s museum display that illustrates concepts of gravity and momentum when children race tennis balls down different tracks.

In their middle two years, undergraduate students encounter the difficult theoretical courses that define them as engineers. To cement the abstract concepts, interdepartmental faculty teams developed interdisciplinary focus courses that capitalize on the state-of-the-art equipment in the two large, open laboratory plazas in the ITLL, shown in Fig. 2. Students gain hands-on reinforcement of the fundamental principles of electronics, fluid mechanics, controls, measurements, structural mechanics, materials, and thermodynamics. These are open design labs that allow first year students to watch the upper class students doing experiments at the lab stations below. In addition, all students get further exposure to the process of engineering design by watching senior design projects unfold in the visible capstone design studios. Examples of these projects include building a race car, constructing award winning autonomous vehicles, and building a human-powered submarine.

A key to adding experiments to theory courses was the development of stand-alone experimental modules. These can be assigned as hands-on homework in theory classes as well as being used, with highly mobile lab setups, as in-class demonstrations. Modules have been developed in all major disciplines.

A. Students

The commitment of CU to ITL begins at the grass roots—with student support. Since the inception of the ITL Program, our students have provided essential and unique intellectual support. Engineering students have also been financial partners in the evolution of the ITL Program since
its beginning, and they continue to play a vital role in the success of the entire ITL Program. In 1991, engineering students voluntarily imposed upon themselves an annual $200 differential in tuition and fees to underwrite the nationally unique Engineering Excellence Fund. The fund generates $700,000 annually, half of which is committed to operational support of the ITL Program. The balance is awarded for curricular innovations throughout the college to faculty, students, and staff by a competitive proposal process judged by a student committee. Most of these proposals involve ITL in some way. In 1994, students lobbied the Colorado state legislature to support the ITL Program and change traditional funding practices so that $478,000 of their funds could be used towards capital construction of the ITLL. Several students served on the original student/faculty curriculum task force that shaped the program, and dozens of students provided input into the conceptual design of the ITLL.

Students continue to hold critical decision-making roles in the ITLL: upper division undergraduates serve as coaches in the first-year engineering projects course, teams of student “patrollers” ensure after-hours security in the facility, and students are helping to develop ethics case studies for incorporation into the first-year design experience. Faculty solicit, respect, and respond to student input. From the beginning, the ITL Program was conceived to be by, and for, students.

III. BUILDING AS LEARNING TOOL

The ITLL was used for teaching as it was constructed and it is currently used as both a home for lab experiments and an experiment in itself. The various BLT features can be grouped into four main levels of complexity.

- **Exposure**: This feature shows, through example, the various engineering systems required to make a building function. Virtually everything required to make the building function is exposed and incorporated as design elements.
- **Measurement**: Sensors permeate the ITLL facility to allow real-time monitoring of the “pulse” of the building, including air flow and temperature, structural strain, electrical demand, soil moisture and temperature, etc. These data are available in real time on workstations located in gallery spaces, and the data from these sensors are continuously monitored and posted on the Internet at http://blt.colorado.edu. As data are accumulated over months and years, clear trends should develop, giving a big-picture look at actual building behavior.
- **Manipulation**: Students are permitted to control the climate of one of two identical side-by-side classrooms and also to experiment with a high-speed, parallel computer network throughout the building.
- **Documentation**: The construction process was documented with video, still images, AutoCAD drawings, structural calculations, and a real-time image of the site posted every 15 min on the World Wide Web (WWW) (http://itll.colorado.edu/Chronology/index.html). A time-lapse video shows the complete construction sequence in a few seconds.

A. Exposure

1) **BLT Interpretive Tour**: We have developed a self-guided tour of the many BLT features of the ITLL using interpretive signs. Text and graphics are located throughout the facility to explain the design of the building and its systems. The goal is to communicate complex technical features effectively in language understandable by children and nonengineers. Examples of visible BLT features on the interpretive tour are described below.

2) **Exposed Building Systems**: In the ITLL, portions of building systems that are normally hidden above ceilings or behind walls are exposed. These include the following.
   - **Mechanical**: Usually hidden, the air handling unit is prominently located on the upper level, accessible to the public. The supply air leaving the air handling unit passes through a single, 5-ft-diameter duct on its way through the maze of ducting that is an architectural design element throughout the building. View windows in the air handling unit reveal moving fans, and a window in an air duct reveals streamers placed inside to help visualize air flow.

   Mechanical equipment, such as pumps, compressors, heat exchangers, etc., is normally hidden from view, but in the ITLL it is visible through large windows, and students may walk through the two mechanical rooms unsupervised. Signs and system diagrams explain the equipment, and various pipes are color-coded for easy identification (Fig. 3). Piping is also visible throughout much of the building. The mechanical room also houses one of the Andover computer workstations that graphically display the functional status of the building systems. Plexiglas on the underside of a variable air volume (VAV) box in one of the classrooms allows students to see damper actuation and the usually hidden components of this standard piece of heating, ventilating, and air conditioning (HVAC) equipment.

   - **Electrical**: Although not accessible to students without supervision, the electrical distribution panels are prominently visible behind windows and feature transparent panels to show their inner workings. Elsewhere in the building, dummy electrical and motor control panels adjacent to functional ones may be manipulated without affecting lab operation. Much of the electrical conduit is visible throughout the building, intentionally designed and carefully crafted to become an architectural design element.

   - **Communications**: Much of the network wiring runs in cable trays suspended from ceilings. While the primary function of the cable trays is to allow easy network access, they also help visitors visualize the extensive computer network. View windows into telecommunications closets and the building computer machine room expose the various wiring systems, boards, and equipment necessary to support extensive computer networks.

3) **Structural**: The structural features of any building are of key engineering significance but are almost always either hidden from view or overlooked by the building occupants.
Fig. 3. Mechanical equipment is color coded to identify different systems.

Fig. 4. Exposed re-bar reveals innermost structure of concrete columns and beams.

a) Variety of structural systems: For educational demonstration purposes, the building has been designed with four different structural types used in more than ten different applications; all are exposed. This includes:

- wide flange steel columns;
- long and short span beams;
- tube steel bar joists and a 40-ft truss;
- composite steel and concrete decking;
- precast concrete;
- cast-in-place concrete;
- load bearing masonry.

b) Visible re-bar: Steel reinforcing bars are integral to the design and construction of concrete structures, but they are only visible during construction. In one location, representational “re-bar” has been applied to the outside of the column to visualize what is embedded inside (Fig. 4). A section of the steel deck attached with anchor studs has been welded onto a prominent steel beam to create a permanent display of the composite floor construction that is hidden from view elsewhere under the concrete and floor tile.

4) General: The most common design goal in a building is to provide an environment that is not intruded upon by the building systems. In the ITLL these systems are exposed.

a) Cut-away walls: The building features cut-away walls enclosed in plexiglass to expose interior wall construction, plumbing, conduit, etc. Other transparent “slices” into the building include glass plumbing pipes in a roof drain, a plexiglass cover on a fire alarm panel, as well as a window into the elevator shaft to show the hydraulic piston and machinery required for door operation. However, the window into the wall between the men’s and women’s restrooms reveals plumbing and wiring, but little else!

b) Acoustical panels: Sound-absorbent acoustical panels are a design feature in the ITLL, as well as a very functional one. Ground-face concrete masonry not only protects the walls, it includes sound absorbing material behind open slits.

c) Light shelves: Horizontal light shelves and vertical fins on the south and west faces of the building serve to shade the interior from harsh direct light and also provide indirect daylighting. Students can track and study solar angles.

B. Measurement

A wide array of sensors located throughout the building connects to the Andover control system used to control building climate. Computer workstations located in several locations feature graphical building layouts and displays of current values of all sensor points, as well as allowing trending of the data. As mentioned earlier, this information is also made available on the WWW (http://blt.colorado.edu).

1) Structural: Gathering detailed data on the structural behavior of the ITLL required careful planning during design and construction.

a) Vibrating wire strain gages: To introduce students to the workings of structural building systems, vibrating wire strain gages were installed in the foundation and column system within the ITLL. The vibrating wire instruments were attached to the reinforcing steel and the concrete was poured around them. Data were gathered showing strain in a caisson.
as load was built up during construction. Using this BLT project, students are able to make measurements in a setting in which they can literally put their hands on the column in which the strains are being measured. They will have the opportunity to make a comparison of theoretical and actual loads. Gages have also been welded to the 40-ft steel truss in the upper Lab Plaza to allow students to see the distribution of tensile and compressive forces (Fig. 5). Finally, vibrating wire gages have also been attached to structural beams and columns supporting the upper Lab Plaza; students can track loads as they are carried horizontally across beams and vertically into columns. Systems have been designed to allow students to apply live loads to both the floor of the upper Lab Plaza and the flange of the truss.

b) Fiber optics cast in concrete: This pioneering project is a good example of the BLT work that was done during construction. In order to instrument the ITLL building to measure structural strain (from occupant load, wind, snow, etc.), a scaled mock-up was built to test and research use of fiber optic technology. With 220 m of fiber donated by Corning, 48 fibers were embedded in three levels of columns and two levels of beams of the building structure as the concrete was poured. The fiber-optic leads will be connected to an optical time-domain reflectometer that is being developed for monitoring by undergraduate students in the ITLL.

2) Electrical: The ITLL is equipped with a state-of-the-art power monitoring system that allows engineering students to obtain data on building energy use and energy patterns. Power Logic software, by Square D Electrical, connects to the Andover system to track large-scale (building) power consumption and small-scale (designated circuits) usage, as well as power characteristics. Students can monitor the building’s electrical distribution system, from main electrical feeders to branch circuits that feed computer classrooms. On screen, or on display panels in various locations throughout the building (Fig. 6), they can see the building’s electrical system come alive and gain valuable insight into the way technology is currently being used in private industry. This system allows students in circuit theory and power courses to monitor power factor and power factor angle as different highly reactive machines are used in the building.

3) Mechanical Systems: The various mechanical systems of a building are usually only visible as ducts and thermostats. In the ITLL these systems are made visible, measurable, and in some cases controllable.

a) HVAC system: Like most modern buildings, the ITLL has a well-engineered central HVAC system. However, several things distinguish our system. While most buildings are only monitored to provide effective system control, our building has more extensive monitoring of individual components and the complete system. At the component level, individual equipment is monitored to allow engineering analysis of its performance. This equipment includes heat exchangers, fans, pumps, and duct and piping systems. For example, two fin-tube heaters are equipped with temperature sensors to measure inlet and outlet water temperatures and air temperatures above and below the heater, allowing measured performance comparisons with theoretical predictions of free and forced convection in heat exchangers. At the system level, the monitoring promotes an understanding of the interactions among the system components. For example, an increase in room temperature will cause a cascade of other system changes, all of which can be traced through the air distribution system, the air handler (Fig. 7), and the chilled water system.

b) The ITLL swamp cooler: Another interesting feature is that the bulk of the building is evaporatively cooled (with the exception of the conventional refrigeration system in the Simulation Lab to ensure the reliability of the high-performance UNIX workstations). In the dry Colorado climate, most summer air conditioning requirements can be economically satisfied by evaporating water into the building air, cooling and humidifying the space. However, at times of high outdoor temperature and humidity, the indoor temperature and humidity are likely to be higher than usual. Using the monitoring in the cooling tower and air handler and fundamental psychrometric relationships, students quantitatively link their indoor comfort to outdoor conditions and system operation.

4) Thermal Environment: In addition to the performance of the HVAC system that controls the building environment, additional temperature sensors were incorporated into the ITLL to characterize the thermal environment.

a) Air stratification: Temperature sensors are arrayed vertically approximately every 8 ft throughout a three-story space to track air stratification.

b) In situ heat conduction: Temperature sensors are embedded 1 in apart through north, east, south, and west facing solid precast concrete walls to study the effects of solar orientation and thermal characteristics of concrete. Sensors are also located at each change of material throughout a composite exterior wall. Knowing inside and outside temperatures, students compare the actual thermal gradient with the predicted one.

c) Soil temperature: Sensors along the exterior of the foundation wall enable students to monitor soil temperature, track freeze lines, study thermal characteristics of soil, and correlate these data to climatic data.

d) Thermal performance of windows: In accordance with current energy conservation principles, most of the glazing in the ITLL is double-pane insulated windows. However, in one area of the lower Lab Plaza, students can compare the thermal performance of several different glazing systems using temperature sensors connected to the Andover system (Fig. 8). This includes conventional 1/4-in single-pane tinted glass (as used on the 30-year-old Engineering Center), as well as more “high tech” double-pane glass with Low-E coating (as used throughout the new ITLL), double-pane fritted (patterned) glass, and triple-pane Heat Mirror® glass.

5) General: A complete understanding of the environmental conditions of the building interior requires monitoring of the general local climate.
teach basic engineering science concepts relating to fluids, thermodynamics, pollutant transport, and aerodynamics, and techniques for analyzing time series of data.

b) Ambient air quality: Students investigate operating principles and practical aspects of ambient monitoring with Environmental Protection Agency (EPA) reference methods, and they gain experience in using regression and time series analysis to better understand relationships between pollutant concentrations and meteorological conditions.

c) Hydrological information: An automated hydrologic monitoring system surrounds the ITLL building. The system consists of soil moisture probes and surface runoff and drain flow measuring equipment. The continuously collected data, combined with data from the weather station, can be used to teach fluid flow, engineering hydrology, groundwater engineering, water resources engineering, and transport processes. Handling the information provides students with experience in data acquisition, data synthesis, data analysis, and use of data in model simulations and engineering design.

C. Manipulation

1) Climate Controls: The two identical first-year project classrooms have different climate control systems. One has conventional pneumatic controls, while the other has separately operable, direct digital controls (DDC) which students can manipulate (within reason!) and measure the effect of changing different variables, such as temperature and air flow. A mechanical VAV box with a plexiglass view panel is installed so that students can see the equipment in operation.

2) Experimental Computer Network: In the ITLL, all computers and data acquisition instrumentation are linked via high-speed networks. The Production Network, using 100 Mbyte/s-based technology, allows students to take...
data at any location and access it from any other location for analysis, simulation, printing, etc. To provide further BLT experiences, a second limited network, called the Experimental Network, using 500 Mbyte/s-based fiber-optic technology, allows students to experiment with the latest in network technology without jeopardizing the integrity of the Production Network.

D. Documentation

1) ITLL Online: Information regarding the construction process was posted on the ITL website (http://itll.colorado.edu) from ground breaking in October 1995 until landscaping was complete in December 1996, including photos of the architectural model, construction schedule, information regarding touring the construction site, and the latest image of the site from a video camera mounted on the Engineering Center. This image was updated every 15 min and the stored images formed the basis for a time-lapse video showing the building rising (magically!) from the ground.

2) Educating Construction Engineers: The college’s Construction Management Program has taken advantage of the ITLL construction project to capture on-site construction lessons to enrich its curriculum for future students. This real-world resource features the principles and practice of construction and will be available for students for years to come. This includes:
   • a collection of real-time and time-lapse video tapes of the construction progress;
   • all construction documentation (AutoCAD drawings, contracts, calculations, memos, meeting minutes, change orders, field clarification requests, etc.);
   • a construction engineering video library (a user-searchable library on CD-ROM of short digital video clips of construction processes, materials, and equipment).

IV. BLT System

Fig. 9 shows the architecture of the BLT system. Data from over 300 sensors distributed throughout the ITLL building are collected on a small number of data-collection computers. On arrival, the data are e-mailed to a central UNIX computer that stores them in a relational database. Users issue requests for data through their web browsers. The browsers send the requests to a web server (http://blt.colorado.edu) which, in turn, triggers the required programs necessary to retrieve and format the requested data.

To facilitate easy location of data, users can search for data from different perspectives. For instance, sensors can be searched by dimension (e.g., temperature, flow, insulation, etc.) or by location (e.g., the air handling unit, the weather station, the cooling tower, etc.). Similarly, any list of retrieved sensors can be sorted according to any of its attributes (e.g., name, number, manufacturer, sensor type, etc.).

Data are available as line graphs (Fig. 10) or as table-formatted ASCII (text) files (Table 1). Whereas the former facilitates easy comparison of the trajectories of variables over time (note the relationship between outer and inner wall temperatures during a 24-h period in Fig. 10), the latter allows inspection and use of the actual, numerical data. Once retrieved, data can be interactively rescaled, zoomed, replotted with different plot types, saved to the local computer, etc.

Table 1 shows an example of the ASCII data that are available on the web from the BLT system.

In addition to the provision of ITLL sensor data, the BLT system contains a large collection of text and graphics explaining the functions and workings of the various building components such as the air conditioning, the building’s structural components, the air handler unit, the glazing, etc. These overviews are partly interactive in that whenever the text refers to a quantity or variable actually measured by one or more sensors, these references are “hot” links which, when clicked, automatically display a graph of the last 50 observations.

V. Virtual Tour of ITLL

As their senior design project in computer science, a group of four students built a virtual tour of the ITLL that will be accessible through a VRML browser on the Internet. “Visitors” will be able to navigate the interior spaces of the ITLL and access sensor data by clicking on flashing icons that indicate the location of the various sensors throughout the building.

VI. Impact on Electrical and Computer Engineering (ECE)

The ITLL is now the site of the labs for the first circuits course and the nonmajors circuits and electronics course. The data-acquisition equipment and software (National Instruments modules and LabView) and Hewlett Packard instrumentation in ITLL has allowed a new level of data gathering and analysis in lab courses. The ECE students also see the use of sensors and data analysis by other engineering disciplines. This exposure shows ECE students the range of disciplines in which their expertise is useful.
Working alongside other engineering students in the freshman design lab and in the same space with other engineering courses forms friendships and interests that manifest in multidisciplinary senior design projects. The simulation lab in ITLL has hosted several senior ECE courses including fields and waves, computer design, and many independent study projects.

The data from the BLT system is used as another source of examples in signal processing courses and in power systems courses. The exposure to time series analysis of nonelectrical signals is especially important in broadening the students’ worldview.

ECE students participate in the freshman projects course and have a deepened appreciation of teamwork and multidisciplinary projects with real customers before they take their first ECE course. This experience increases both their demand for real-world applications and their appreciation of the limits of their knowledge and the power of analysis and modeling techniques.

VII. GENERAL COMMENTS

The ITLL and associated curriculum changes, especially the freshman projects course, have had a profound influence...
on our students. The retention rate into and through the junior year is markedly higher (a tremendous assessment effort has been a continual part of ITLL activities). The use of data acquisition and analysis, together with special experimental modules, have given our students significantly more real-world experience, which has resulted in more summer industry intern positions and more satisfaction by students and employers. The manufacturing center and the ability to physically realize their designs has excited students and faculty and reinvigorated many courses, including senior projects.

At present our use of the BLT system is primarily demonstrative. Students in different classes build software to show building performance. Some analysis relating different building system data is done, but much more is possible. Detaled experimentation with the building systems is not yet commonplace. However, students clearly appreciate analyzing data on “their” building.

The ITLL as a building laboratory instrument and teaching paradigm is still growing and changing. In its second year of operation, ITLL served over 3218 students (registrants) during two semesters in 99 courses taught by 76 faculty. The building is completely programmed in the summer with K–12 outreach activities. The ITL paradigm has motivated aerospace engineering to completely redesign its curriculum. Other departments are rapidly responding to the new possibilities.

Much has been accomplished, but the potential for future growth and evolution is even greater. We have truly shaped a building that is, in turn, shaping us.

VIII. CONCLUSION

The ITL paradigm and facility are rapidly, profoundly, and positively affecting our curricula, students, and faculty. The various BLT features of the ITLL provide unique opportunities to learn about a variety of engineering principles as utilized in a modern structure. The concepts are being included in the curriculum in a variety of classes, ranging from construction management to a digital signal processing class utilizing the various pieces of sensor data. The capability to make this information available on the WWW offers the potential for a truly worldwide learning opportunity.

IX. FOR MORE INFORMATION

For an online discussion of this special issue, please visit the discussion website at http://ieee.research.umich.edu.

REFERENCES


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