Lessons Learned from Monitoring Electricity Consumption in a Research Lab Through a Capstone Project Course

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ABSTRACT

This paper describes the experiences and lessons learned by a team of Civil and Environmental Engineering graduate students during a capstone project-based course, which orients students to acquire knowledge on sensing technologies, data management, systems engineering, and visualization concepts in order to design and implement an energy monitoring system in a three room lab space. The team, mentored by faculty members, was responsible for the deployment of hardware, establishing communications, database design and implementation, and developing visualizations to communicate the relevant information based on the requirements of a client role-played by a faculty member. Lessons learned from this project include the importance of applying a systems engineering approach during the iterative scope definition and design processes, and the use of alternative communications, learning, and problem-solving methods in order to tackle challenges of larger scope and complexity than presented in classroom-setting coursework, while working on a team environment.

INTRODUCTION

Each year, the Advanced Infrastructure Systems (AIS) graduate program at Carnegie Mellon University (CMU) offers an interdisciplinary graduate level capstone project course. This course is intended to prepare students to work on ill-defined, open ended, and industry-driven project settings, while focusing on “sensor data-driven and intelligent systems, components, devices and processes that improve the performance and/or reduce the life-cycle cost of a broad range of physical infrastructure systems” (Garrett 2005).

The project for a recent academic year consisted of defining and implementing the required infrastructure to collect, store, query, and visualize “real time" electricity consumption data in a three room research lab at CMU. The team consisted of seven master students at Civil and Environmental Engineering Department with different backgrounds and interests; one faculty member acting as "client", defining scope of work and requirements; and one faculty member mentoring the team, facilitating the necessary resources and assisting on project design and implementation decisions.

Several experiences have been published on the use of capstone projects as tools to enhance the learning experience of students, (e.g., Longstreet et Al 2013, and Werner el Al 2013), not only in engineering programs but in other areas as well, such as in computer science. In all cases, as in this one, course designers have the main objective of offering students a learning setting based on collaboration, teamwork, and pro-activeness in the solution of industry based problems, using the fundamental knowledge acquired during their studies. The authors would like to contribute to the understanding of the benefits of project courses by sharing in this paper the challenges faced and lessons learned during the execution of this project. A summary of the project-specific deliverables and components are also discussed in order to provide the reader with sufficient context on the challenges and the approaches taken in the delivery of the end product.

ELECTRICITY CONSUMPTION MONITORING SYSTEM

The general objective of the project was to deliver an electricity consumption monitoring system that provided near real-time data of consumption at the Pennsylvania Smarter Infrastructure Incubator (PSII) Lab, presenting it in a meaningful way to the end-users of these monitored spaces. This 1,150 sqft lab consists of three working rooms (one conference room, one computer lab, and one room for research in virtual reality) and a small mechanical room. Figure 1 shows a 3D representation of the research space being monitored.

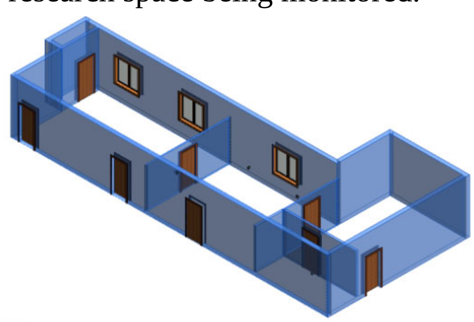

Figure 1. 3D Model of the Pennsylvania Smarter Infrastructure Lab at Carnegie Mellon University.

The project included the installation of sensors in order to acquire real time data, establishing the communications between the sensors and the databases, and creating all required databases and visualization templates per client's requirements. The students gained experience in working with plug-level power meters (i.e., FireFly sensors [Rowe et Al 2006]), circuit level sensors (i.e., Enersure), and sensor network servers (i.e., Sensor Andrew [http://sensor.andrew.cmu.edu], and PI System [http://www.osisoft.com]).

After applying a systems engineering approach, which included requirements capturing, analysis, design, implementation and verification/validation phases, the students decomposed the project into several tasks and managed the project time and deliverables throughout the semester. The students were able collect, store and visualize data via sensors by implementing a web-based visualization interface leveraging time-series graphing Javascript libraries (HighCharts), and using SQL embedded in PHP to query data. A relational database was designed using and implemented using MySQL to store the data. While the scope of the project was ultimately reduced, the students gained experience working with each system. The following sections describe each of these challenges and approaches taken to overcome them in order to achieve the final product.

COMPONENTS OF THE PROJECT, CHALLENGES AND LESSONS LEARNED

General Team Structure. The student team was largely afforded with the freedom and responsibility to act independently, and critical team decisions for this project included: the organizational structure and project delivery approach. Following the systems engineering approach (requirement identification and documentation, design synthesis, verification, validation and testing) the team was able to break down the project into sub-tasks.

The work breakdown structure (WBS) included tasks related to: (a) project management, (b) sensor deployment and data acquisition, (c) data management, and (d) visualization. The team was set up to include one project manager, and subgroups' coordinators in charge of each of the WBS component. Students also rotated within each subgroup in order to learn all aspects of the project. In allowing students to contribute to multiple subgroups, the team attempted to allow each member to understand as many aspects of the project as they desired, while working diligently to achieve the client's satisfaction. The scope of work, challenges and the lessons learned associated with each task is provided in details in corresponding subsections below:

Project Management. The project management activities focused on scope definition, team organization, time management, resource management, and communication with the client. Although students take data acquisition, data management, data modeling and programming classes as part of the graduate curriculum, implementing a project that demands revisiting and applying these skill sets in an integrated fashion required a longer orientation time and planning for the students as compared to a regular class project. The learning curves for many aspects of the project made it particularly challenging for the team to meet some projected schedules. One of the important lessons learned, from the project management perspective, was the importance of having the client on board early on to identify the functional requirements of the end product. Ultimately, the iterative approach of identifying, designing, prototyping system features and getting client feedback was essential in ensuring project progress.

Sensor Deployment and Data Acquisition. The sensor deployment and data acquisition team was tasked with installing circuit and plug-level sensors and making the necessary connections (e.g., writing software drivers) to acquire the electric consumption data at the circuit and plug levels. The hardware used included one Enersure Branch Circuit Power Meter made by Trendpoint (Figure 2.a), and three Firefly plug sensors (Figure 2.b). The Enersure was installed in the electrical sub-panel serving the PSII Lab. Each Firefly sensor is capable of monitoring real-time consumption of one outlet. These sensors transfer the data wirelessly to the server, providing measurements every second.

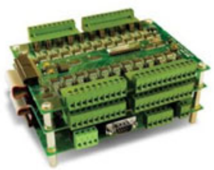

Figure 2. Data Acquisition Hardware (a) Enersure (Source: Trendpoint Website 2013), and (b) Firefly(WiSE Lab Website 2013)

The team successfully installed the plug level sensors and established the connections to start collecting data in a local database. An important step for the sensors to communicate with the local database was to write software drivers for each sensor type. The sensors were setup such that the data would be polled each second.

Data Management. Once the sensors were installed and the data acquisition setup was prepared, the next step was to enable storage of the collected data. The data management subgroup was tasked with storing data on a local machine and on a pre-installed commercially available server. Each task had unique challenges as discussed in the following sections.

MySQL. After exploring several options, the team decided that MySQL would be the most favorable database management system for the project, due to the pre-existing familiarity of team members with relational databases, ease of compatibility with Linux operating systems for the Firefly sensors, affordability (open source), and wide use in developing database driven web applications. The main challenge for the database team was creating an efficient database design in order to meet the storage and visualization requirements.

The most important lesson from this task was the development of data reduction strategies. Since data was being collected every second and visualization required real time data, the team noticed that queries response times increased as the days passed, which is why data reduction strategies were implemented in order to store only the required data necessary for visualization purposes. In the process of implementation, the team became increasingly aware of the challenges and trade offs that occur in maintaining a database that meets the performance requirements. Establishing communication between the hardware team, the data management team, and the visualization team was essential for arriving at the final design.

Commercial Server. The team was given access to a commercially used data management system, PI System, in order to use an information system specifically designed to manage large amounts of data and compare it's performance against the one created by them. The main challenge associated with this task was to establish the connection between the sensors and the server. After several failed attempts to establish a connection to store the data from the sensors in the server, the team interacted with the technical support team of the system supplier.

While the connection failures were not completely resolved by the project completion time, the interaction with PI System tools generated very important experiences for the team: from approaching and communicating problems to persons that are not specifically involved in the project, but have the expertise on relevant components, to appreciating the benefits of the features that allow such tools to manage the data in a more efficient way (after having to deal with the challenges described in the MySQL section).

Visualization. The last step of the project was to develop a graphical user interface that would show the energy information in the forms specified by the client. The visualization team was tasked with collaborating with the client to create an electricity consumption dashboard for the laboratory space. To do so, the team conducted a literature review, explored similar monitoring systems on campus, and proposed prototypes that would meet the goal of communicating relevant electricity consumption information occurring in the three-room laboratory space. After discussions with the client, the visualization platform was changed to a hallway monitor display instead of an interactive website. While the website design would have been designed to provide options and flexibility to a visitor, with a focus on access to historical data for analysis, the new design focused on displaying "real-time" data in ways that would be easily appreciated by passers by. Thus the final design was created to display a dynamic gauge of "real time" data, a time series that shows the electric consumption for the last three minutes, current day hourly electric consumption averages combined with historic daily hourly consumptions averages, current weekly daily averages with historic averages for benchmarks, and the sensor locations. The final dashboard can be seen in Figure 3.

While the design was fairly simple, the team learned to modify free interactive chart libraries and generate SQL queries to access the data from the MySQL database. In doing so, the challenge of "real-time" became apparent as the system was not designed to display data each second, but instead every fifteen seconds as a result of the lag in querying the data. The change in the platform also proved as a learning experience on the differences in design of electricity monitoring systems for each application.

SUMMARY OF LESSONS LEARNED

This capstone project class proved that even if students learn the fundamental technical concepts required to deliver an energy monitoring system (e.g. sensor deployment, data acquisition, and data modeling and management), additional skill sets are required in order to work in teams and deliver a wide scale project, which are usually not addressed in traditional engineering class settings. Such skill sets include: the ability to do research, being proactive and self-intrigued for each project task,

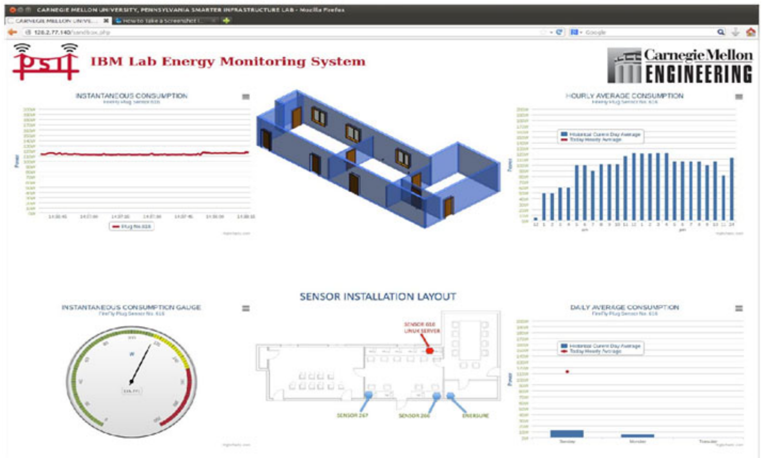

Figure 3. The final dashboard design

articulate problems and communicate challenges to team members and external parties, search for a solution space for each task and evaluate options, and ability to divide project scope into tasks that still enable implementation of an iterative approach for delivering the end product.

This experience also showed the importance of having close communication with the client is essential in the project scope definition process. Interaction should start early on and maintained throughout the design and execution phase in order to ensure a proper understanding of the client's expectations and the functional requirements of the end product. This is an important lesson that students should be aware of while they prepare for the professional and real-life projects. Having an integrated (where all tasks are considered concurrently rather than sequentially) and iterative approach (having establishing a functional prototype across tasks with a subset of requirements and getting feedback to finalize it) are essential for successful delivery of projects.

Throughout the design and implementation of the energy monitoring systems, students realized that understanding all compatibility issues between data storage and data acquisition platforms, and making effective selections of system components, is a very important task. Additionally, students experienced that there are several issues that could affect the quality and reliability of the final product (e.g., power outages), and that a system shall consider preventive and corrective measures in order to automatically overcome the problem if it arises. In relation to data storage for energy monitoring systems, data reduction strategies play a critical role and decision on how to store the data should be made based on how the data will be used by the downstream parties, as was the case for this year's project.

From the learning perspective, the most important lesson was that there are multiple ways of gaining the knowledge required to deliver a multidisciplinary project, and although they are readily available, it requires a proactive attitude and good communication skills in order to get the best out of all of them. The following is a summary of approaches used by the different team members in order to solve the different challenges faced:

- Interaction with domain experts who acted as consultants for the team: different professors and students from the departments of Electrical and Computer

Engineering, Architecture, and Civil and Environmental Engineering, and technical personnel from CMU's facility management were consulted.

- Interaction with manufacturers: the team found that communicating with technical support personnel of companies that supplied hardware and software was an effective way of overcoming obstacles. Experiences included discussing problems over the phone with Enersure manufacturers to receiving the visit of a technical support representative of OSIsoft to solve problems with PI Server communications.
- Use of online tutorials: the availability of tutorials and comprehensive user manuals was a critical success factor on the selection of tools such as: MySQL, PHP, Highcharts, and PI Server.
- Use of online collaborative sites: especially while creating the source code for the different software components, the use of online communities such as StackOverflow (http://stackoverflow.com), was extremely useful.

While using the different approaches mentioned before, another great learning experience was having to communicate the problems or the challenges that needed to be overcome to parties that were not familiar with the project but that had the required expertise to help. Usually these sources would be consulted while trying to solve a problem in a component of the project; however, team members learned that in a system based project it is always of great importance to keep in mind that any solution in any part of the system has to be compatible with the other elements.

The compatibility requirement in a systems based project lead to another important lesson: continuous communication between the different team members, and the client, as well as flexibility and creativity in the problem solving process is of great importance. Solutions in one component might require changes in other parts, a project like this one required to think in what was the best for the system and not what was the best for the sub group.

CONCLUSIONS

Through the collective effort of the students and mentors the AIS capstone project offered a wide variety of takeaways unique from their previous courses. The team successfully implemented an electricity monitoring system that collected data, managed the data, and provided a useful visualization in the form of a dashboard. In doing so, the students gained valuable insights specific to the process required to implement an electricity monitoring system, important factors to consider in the design, as well as identifying areas for further improvement. Likewise the project offered real world project experience that could be translated to other projects, such the importance of communication, and the application of systems engineering and iterative design approaches. Students also benefited from experiencing the challenges from applying their technical skills on a large-scale project, and built confidence in being self-motivated problem solvers.

Currently, to measure the student performance several metrics and deliverables are utilized throughout the semester. Overall performance is measured based on the success of the project and submission of the project deliverables. In addition, students are responsible for weekly presentations for progress update to project mentors and submit weekly progress reports. As a future work, comparative metrics can be defined to enable measurement of student performances in team based project settings and regular class settings.

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