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Data-Driven Research Experience for Undergraduate Students

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ABSTRACT

Data analysis is essential to modern engineering systems and processes. With advanced computational tools, large datasets can be stored, processed, and analyzed to uncover key characteristics and trends. Developing the ability to make data-driven inferences and predictions is a crucial skill for today's engineering students. This paper discusses the integration of innovative Artificial Intelligence (AI) deep learning techniques into undergraduate research at a teaching-focused institution, with an emphasis on data mining and infrastructure performance prediction.

The research projects highlighted in this paper involve analyzing Connecticut's bridge inventory and inspection data for forecasting bridge conditions, as well as examining driver behavior, including speed profiles and gap acceptance at roundabouts in Connecticut. These projects are either internally and externally funded, providing students with opportunities to engage in research during the summer, throughout the academic year, or as part of their independent study courses. Some key student research tasks in these projects include data collection, data cleaning, contextualization, analysis using AI neural networks, and result interpretation and presentation. Students are given multiple opportunities to present their work, including at the University's undergraduate research colloquium, progress meetings with Connecticut Department of Transportation (CT DOT) staff, and at local and regional conferences.

This paper uses these projects as case studies to demonstrate how data-driven research experiences can be successfully integrated into undergraduate education, particularly at teaching-focused institutions without Ph.D. students. A survey was conducted among both current students and alumni who participated in these research projects, evaluating the impact of the experience on their technical skills, self-confidence, and ability to work independently. The survey results indicate that students reported significant improvements in time management, research skills, and self-confidence. These findings reinforce the hypothesis that data-driven research experiences contribute to both academic growth and the development of lifelong learning skills. In conclusion, this paper provides insights into how undergraduate students at primarily teaching institutions can benefit from hands-on, innovative data-driven AI research experiences. It also offers potential strategies for incorporating these valuable skills into future undergraduate research opportunities, enhancing student engagement and learning outcomes.

INTRODUCTION

Data analysis plays a pivotal role in modern engineering systems and processes. With the advent of advanced computational tools, the ability to store, process, and analyze large datasets has become a core skill for engineering professionals. Recognizing this need, teaching-focused institutions like ours are integrating innovative Artificial Intelligence (AI) techniques into undergraduate research to equip students with these essential competencies. Undergraduate

research experiences have been shown to significantly enhance students' learning, technical skills, and confidence, as highlighted by Lopatto (2017) [1] in the Survey of Undergraduate Research Experiences. Such experiences not only provide a platform for applying theoretical knowledge but also foster critical thinking and problem-solving abilities, essential for future engineering professionals. The research has shown that data-driven research experiences contribute to both academic growth and the development of lifelong learning skills.

Linn et al. (2015) [2] emphasize the transformative impact of undergraduate research on students' career trajectories and academic growth. They argue that these experiences create opportunities for students to engage with real-world challenges, build collaborative skills, and develop an appreciation for the research process.

Maybee et al (2015) [3] discussed the integration of data informed learning within disciplinary contexts. By building upon students' prior experiences and aligning data usage with subject-specific learning, the framework fosters both academic development and the cultivation of lifelong learning skills. The approach encourages active engagement with data, promoting critical thinking and adaptability essential for continuous learning.

Kleimola & Leppisaari (2022) [4] explored the application of learning analytics to foster future competencies in higher education. By leveraging data-driven insights, the study demonstrates how personalized learning experiences can enhance academic growth and prepare students for lifelong learning. The integration of analytics into educational practices supports the development of skills such as critical thinking, adaptability, and self-directed learning.

Aligned with these findings, this paper develops and supports the hypothesis that data-driven research experiences contribute to both academic growth and the development of lifelong learning skills. It presents case studies focused on analyzing Connecticut's bridge inventory and inspection data to forecast bridge conditions using data mining techniques and artificial intelligence (AI). For over half a decade, I have collaborated with undergraduate students on various aspects of these projects. These efforts showcase how data-driven research can enhance student engagement and learning outcomes, particularly at teaching-focused institutions without Ph.D. programs.

AI RESEARCH CASE STUDIES

Bridge Inventory Analysis

Bridges serve as critical structures within an infrastructure system and require regular inspections to ensure they are in safe operating condition for the public. As of 2010 there are approximately 600,000 bridges in the United States and more than 40% of the bridges are either structurally deficient or functionally obsolete according to the Federal Highway Administration (FHWA) report [5]. Inventory and inspection data have been collected on more than 6,000 bridges in the Connecticut and maintained in databases by Connecticut Department of Transportation (CT DOT) over the past twenty years. The objective of this research is to study the database, examine data patterns and make predictions of future bridge condition ratings using statistical analysis modeling. The research will investigate the correlation between bridge structural deterioration

conditions (e.g. deck, superstructure and substructure) and bridge & traffic characteristics (e.g. bridge age, average daily traffic volumes, number of spans, materials, type of design, etc.) It is expected that insight obtained through this study enables more effective and efficient design and management of bridges.

Roundabout Driver Behavior Analysis

Understanding driver behavior at roundabouts is crucial for improving traffic safety. This project analyzes behavioral data, including speed profiles and gap acceptance, to model and predict driver decision-making. By leveraging AI and data mining techniques, students explore trends that can inform the design of safer roundabouts.

These projects began on a small scale through internal university funding, as exemplified in Figure 1. A sophomore Civil Engineering student and I collaborated on this initiative using an internal Student Government Association (SGA) grant. The student worked on testing smaller-scale predictive models with a three-year dataset using MATLAB's Deep Learning Toolbox. Over time, several Civil Engineering students have contributed to this research under my supervision.

Subsequently, the projects received external funding from the Connecticut Department of Transportation (CTDOT) and the Federal Highway Administration (FHWA). Several additional engineering students were recruited to participate in these efforts. Under my guidance, students typically carry out the following project tasks:

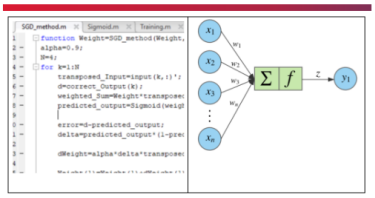
CETA Faculty and Student Receive SGA Academic Research Grant Award

APRIL 16, 2020

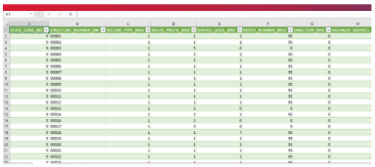
Submitted By: Stephanie Fengler

The College of Engineering, Technology, and Architecture (CETA) is excited to announce CETA faculty member Clara Fang, professor in civil engineering, and Sydney Lewis '22, a civil engineering major, have been awarded a Student Government Association (SGA) Academic Research Grant Award. The grant will allow them to pursue their research work in modeling bridge deterioration conditions using artificial intelligence (AI) to better our local infrastructure.

The project will apply AI, especially neural networks, to better understand bridge inspection data and predict future bridge conditions as public infrastructure deteriorates over time. The neural networks program will be used to analyze data and provide results on which bridges will require maintenance and inspections to ensure all continue to work safely and efficiently. The trained network will allow the computer program to calculate a rating of a bridge's condition in Connecticut based on variables recommended in the National Bridge Inventory (NBI) from the Federal Highway Administration (FHWA) and Connecticut Department of Transportation.



Neural Network Application in Matlab



Bridge Inspection Data

Lewis has been working on testing in smaller scaled examples using Matlab Deep Learning toolbox this Spring. She had some success in testing neural network variables to achieve a satisfactory result. Next, the research team will work on expanding their program to import and analyze bridge data from multiple years. The factors considered include bridge identification information, bridge types, operational conditions, bridge geometric data, functional description of the bridge, inspection data, etc. We expect the result of the project will provide useful information to the Connecticut Department of Transportation on the bridge management system. As part of this project, Fang will also be using the research gathered and project data to help in developing a course to introduce students to AI applications in engineering.

Figure 1. Student and Faculty Engagement Research in AI Neural Networks for Modeling Bridge Deterioration [6]

Task 1: Collect and Contextualize Data: The task includes meeting with bridge inspection engineers and CT DOT staff in order to understand the significance and reliability of data. A multi-year (3~5 years) data set for inspection results of Connecticut bridges will be acquired.

Task 2: Data Cleansing: Data cleansing involved reviewing the available data to check for and attend to unnecessary, erroneous, or incomplete information in order to optimize the analysis.

Task 3: Data Analysis: Three different regression models will be developed: a linear model, a non-linear parametric model and a non-parametric model. The models also consider a variety of explanatory variables. The descriptive statistical summary resulting from the exploration of the database will also be provided.

Task 3: Summary and Results Presentation: The project results will be communicated with the CT DOT. In addition, a research plan involving a long-range duration of data (e.g. over 10 years) combined with other pertinent databases (e.g. environment) will be proposed and submitted to the CT DOT applying for external funding. The student will contribute to writing this proposal and other research paper.

The students will walk through each stage of this analytics pipeline that enables them to collect, clean, understand, model, and report data analyses. By paying close attention to data patterns,

the stories behind outliers, relationships among data sets, and the external factors that may have affected the data, it is expected that this data-driven research will enhance the students' analytical skill and their experience in data analysis may give them the competitive edge in industry.

METHODOLOGY

To provide meaningful research experiences, I have implemented a structured approach:

1. **Project Identification:** Projects were chosen for their real-world relevance and potential to utilize AI techniques. For example, bridge condition forecasting relied on CT DOT datasets, while the roundabout study used driver behavior data.

2. **Student Recruitment and Training**: Undergraduate students were recruited through internal and external funding opportunities. Training sessions covered data collection, cleaning, and analysis using neural networks and other AI techniques. Workshops on interpreting and presenting results were also provided.

3. **Data Collection and Analysis**: Students collected data through fieldwork and secondary sources. For bridge condition forecasting, data was cleaned and contextualized before applying deep learning models. Similarly, the roundabout project utilized behavioral data to identify trends and model predictions.

4. **Feedback and Iterative Improvement**: Students presented their findings during progress meetings with CTDOT staff and at the University's undergraduate research colloquium and other local/regional conferences. Feedback from these presentations informed subsequent iterations of the research.
5. **Assessment**: A survey was conducted among participating students and alumni to evaluate the impact of these experiences on their technical skills, self-confidence, and independence.

SURVEY

A comprehensive survey was administered to evaluate the impact of participating in these research projects on students' academic, professional skills and career path. The survey targeted both current students and alumni who had engaged in these initiatives.

Survey Demographics:

The survey included six respondents: one current student and five alumni, all of whom had actively participated in the research projects. The respondents represented a diverse range of academic levels and involvement. Among the alumni, three had graduated with BSCE degrees, obtained FE licenses, and are now working as engineers in the industry. Two continued their education to earn Master's degrees before pursuing careers as engineers, while one transitioned

into a data analytics role at a public agency. Additionally, one student was accepted into a Ph.D. program, where they continue to explore research in AI and structural analysis.

Survey Design and Questionnaires:

The survey was designed to evaluate the influence of research experiences on technical skills, career readiness, and personal development. Below are examples of the questions included in the survey:

Technical Skills:

How did your participation in the AI research projects enhance your proficiency in data analysis and computational tools? (Rating: 1 = No improvement, 5 = Significant improvement)

Which specific AI or data analysis techniques learned during the projects have you applied in your academic or professional career?

Career Preparation:

Did your involvement in the research projects influence your decision to pursue graduate studies or specific career paths? (Yes/No; Please elaborate)

How relevant were the skills you acquired to your current job or academic pursuits? (Rating: 1 = Not relevant, 5 = Highly relevant)

Personal Development:

How has your participation in the research impacted your confidence in tackling complex engineering problems?

In what ways did presenting your research findings improve your communication and presentation skills?

Overall Experience:

What aspects of the research experience were most valuable to your growth as a student or professional?

Are there any areas where you feel additional training or resources could have improved your experience?

The survey results highlight the significant impact of the research projects on students' academic and professional trajectories. Respondents reported enhanced technical skills, greater confidence in solving complex problems, and a better understanding of AI applications in civil engineering. Many credited their research experiences as pivotal in shaping their career paths and academic achievements, including the pursuit of advanced degrees and industry roles.

Key findings are summarized below:

- Time Management**:** 83% respondents reported significant improvement in their ability to manage time effectively, attributing this to the structured nature of research activities and deadlines.
- Technical Skills**:** All participants indicated enhanced technical skills, particularly in data analysis and AI methodologies. Alumni highlighted how these skills directly and indirectly contributed to their professional success.
- Self-Confidence**:** All respondents experienced an increase in self-confidence, especially in presenting findings to varied audiences, including academic and industry professionals.
- Independence**:** 83% noted greater independence in tackling complex problems, reflecting the problem-solving and critical thinking skills developed during the projects.
- Qualitative Feedback: Respondents expressed appreciation for the real-world relevance of the projects. One alumnus stated, "The research experience gave me a significant edge during job interviews, showcasing my ability to apply theoretical knowledge to practical challenges."

These results reinforce the hypothesis that data-driven research experiences contribute to academic growth and foster essential professional competencies.

RESULTS

The research projects yielded both technical insights and significant student development outcomes:

- **Technical Achievements**: For the bridge inventory project, predictive models achieved an accuracy of 93% in forecasting future bridge conditions. The roundabout study revealed critical insights into driver behavior patterns, informing recommendations for traffic safety improvements.
- **Student Learning Outcomes**: Survey results indicated substantial gains in time management, research skills, and self-confidence. Students reported that their ability to analyze and interpret data greatly improved, while their confidence in presenting research findings also increased.
- **Engagement Opportunities**: Students presented their work at local and regional conferences, including interactions with industry professionals and policymakers, which enriched their professional experience.

DISCUSSION

These case studies highlight the value of integrating data-driven research into undergraduate education. Below provides some key observations:

- **Scalability**: The approach is scalable to other institutions and research areas, given the availability of relevant datasets and computational tools.

- **Skill Development**: Engaging students in hands-on AI and data science projects fosters lifelong learning skills, such as critical thinking, problem-solving, and effective communication.
- **Collaboration**: Partnerships with organizations like CT DOT provide students with practical exposure and demonstrate the societal impact of their work.

Challenges encountered included limited computational resources and the steep learning curve associated with advanced AI techniques. Addressing these barriers through targeted training and resource allocation will be crucial for broader adoption.

CONCLUSION

This paper illustrates how data-driven research experiences can transform undergraduate education at teaching-focused institutions. By engaging students in meaningful, real-world projects, we can equip them with the technical and professional skills necessary for their careers. Future work will focus on expanding these opportunities to include interdisciplinary collaborations and exploring new AI applications in engineering education. The strategies and findings presented here offer a roadmap for institutions seeking to enhance their undergraduate research programs through data science and AI.

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