

# A STEM REU SITE ON THE INTEGRATED DESIGN OF SENSOR DEVICES AND SIGNAL PROCESSING ALGORITHMS

*Andreas Spanias and Jennifer Blain Christen*  
SenSIP Center, School of ECEE, Arizona State University

## ABSTRACT

Arizona State University (ASU) established an NSF Research Experiences for Undergraduates (REU) site to embed students in research projects related to integrated sensor and signal processing systems. The program includes both sensor hardware and algorithm/software design for a variety of applications including health monitoring. The site was funded in February 2017 and the Co-PIs recruited nine students from different universities and community colleges to spend the summer of 2017 in research laboratories at ASU. The program included structured training with modules in sensor design, signal processing, and machine learning. Cross-cutting training included research ethics, IEEE manuscript development, and building presentation skills. Nine undergraduate research projects were launched and the program went through an assessment by an independent evaluator. This paper describes the REU activities, modules, training, projects, and their assessment.

**Index Terms**— Sensor and circuit design, signal processing, machine learning, undergraduate research.

## 1. INTRODUCTION

This paper describes a program providing undergraduate research experiences in sensor devices and signal processing at Arizona State University (ASU). This three year research experiences for undergraduates (REU) site is hosted by the ASU main campus and trains nine undergraduate students per year during the summers for eight weeks. The title of this unique program is Sensor, Signal and Information Processing (SenSIP) Devices and Algorithms REU, and the focus is on integrative research experiences at the overlap of sensor device design and algorithm development. The program includes projects under the auspices of the SenSIP center, a Phase 2 NSF Industry/University Cooperative Research Center site of NCSS. In the first year (summer 2017), students worked with faculty mentors on REU projects. REU students were embedded in different labs and worked on research projects with graduate students. The program also included structured video-streamed and face-to-face lecture modules that provided training in sensor devices, signal processing algorithms, and machine learning. The REU also had training modules in crosscutting areas including ethics, patent development, and standards.

## 1.1 REU Site Objectives

The objectives of the REU site are to: a) introduce students to general research practices; b) engage students in research associated with the integrated design of sensor devices and signal processing methods; c) motivate REU students to innovate and pursue research careers by enrolling in graduate degree programs; d) train students to present their research to stakeholders; and e) building awareness on social implications, ethics, policy, and standards.

## 1.2 Targeted Student Participants

One of the goals of the REU site is to recruit, train, and motivate students to pursue thesis-oriented research programs. We targeted students from several STEM fields including Electrical Engineering, Computer Science, Physics and Mathematics. A special effort was made to attract students from minority serving institutions, community colleges, and state and private universities that do not have a research degree program.

## 1.3 Intellectual Focus

Several modern applications use inexpensive sensors to address health, security, and IoT challenges and applications by using corrective algorithms and software to improve precision and detection accuracy. A key motivation for the REU was to take steps towards preparing a workforce that is well aware of both sensor hardware and algorithm/software methods. The directors of the REU wanted algorithm developers to understand sensor device limitations and sensor designers to understand basic signal processing algorithms. The REU program immersed students in both tasks through lab work and modules (Fig. 1).



Fig. 1 Integrated sensor device design and algorithm development. Algorithms include denoising, feature extraction, machine learning and fusion.

This REU program required students to take online modules prepared by faculty mentors to build their awareness in each research field and in crosscutting areas. The overall REU project has a strong interdisciplinary component as sensor design and algorithm development overlap several

disciplines including physics, chemistry, engineering, computer science, and mathematics.

## 2. REU ORGANIZATION

Students were recruited in the early spring of 2017 and started their research in June of 2017. A diverse cohort of students were recruited including four women, two African Americans, three Hispanic and two US veteran students. Students completed modules including hands on software labs on a weekly basis and responded to assessment quizzes. REU modules included: lab safety; introduction to research; sensor device and circuit design; signal pre-processing and machine learning; software implementation; intellectual property and patents; cross-cutting ethics, standards, and policy; project reports and presentations; and scientific (IEEE style) manuscript development.

### 2.1 REU Project Experience

Students chose a project and a mentor planned and monitored the tasks and outcomes of each project. Students had the freedom to innovate and test ideas. Each REU student collaborated with a resident graduate student who was the immediate graduate mentor. REU students reported their results in IEEE format documents to provide experience with publication formats and logistics. Students gave short weekly updates in the form of a short talk with accompanying slides to the faculty and graduate mentors who provided feedback and further guidance. The students presented a concept poster at early in the program to graduate students, faculty, and industry experts to obtain feedback on their summer research endeavors. A final formal report, a 4-page IEEE style formatted report, was submitted. The students also presented their results in a culminating event with academic and industry attendees including flash talks and poster presentations. The REU directors, project mentors, and the evaluator provided feedback on the final reports and poster presentations.

### 2.2. Timetable of the Research Experience

REU students were immersed in designated project labs with planned weekly tasks and milestones and project aims established by the mentors. The challenge of integrative design of sensors and algorithms was emphasized in all projects. Students worked with their faculty and graduate mentor who guided them through experiments with prototype sensors and with analysis of data using signal and data processing software. Students used machine learning [1] and signal processing tools from MATLAB and other platforms. Students reported their findings to their faculty and graduate advisors weekly. The program also included informal collaborative sessions across labs, weekly seminars, and post-seminar networking with faculty.

### 2.3. Nature of Student Activities

We adopted a strategy that had: a) research modules (see Table A), and b) extensive hands-on laboratory projects. We selected faculty with integrative multidisciplinary research programs funded by government and industry.

Students spent time in two types of laboratories to obtain both hardware (sensor/circuit) and software (algorithm) experiences. The faculty advisor along with the PIs ensured research training and tasks were provided for each student.

Table A. Modules and Schedule for the SenSIP REU Site

Week	Modules	Project	Weekly Deliverable
1	Introduction to Research Protocols, Safety	General Overview of Projects / Deliverables	Quiz on lab; plan proposal outline.
2	Sensor Device Design	Meeting with Mentor	Proposal Abstract, Presentation
3	Circuit Design for Sensors	Project Starts	- Module Quiz - Weekly Report
4	Signal Processing / Machine Learning Tools	Literature Review Project Research	- Module Quiz - Weekly Report
5	Patent Preparation and SBIR Proposal Module	Literature Review. Project Research	- Module Quiz - Weekly Report
6	Cross cutting Ethics, standards and policy	Project Research Continues	- Module Quiz - Weekly Report
7	Presentation Practice Final report preparation	Project Research Continues	- Module Quiz - Weekly Report
8	REU workshop	Research Ends Final Report	Final Presentation; Overall Evaluation

### 2.3. Approach to Undergraduate Research

Lessons learned from past engagement of the Co-PIs and faculty mentors in prior REU, REV and RET supplements with undergraduate and teacher co-authors [2-5] helped establish tasks with outcomes. Students were encouraged to define research objectives that would lead to a paper by presenting examples of past successful REU projects. One of the REU goals is to sustain undergraduate interest in research after the summer experience and motivate students to attend graduate thesis programs. The prospect of REU students generating IP (patents) was enhanced by a seminar in patent and IP development by an expert.

### 2.4 Algorithm Simulations and Experiments

The students were exposed to noise removal techniques, feature extraction, and sensor fusion. Baseline examples were established for their simulations, and machine learning algorithms were used for classification. The accuracy and complexity of different algorithms was evaluated by students under the guidance of the advising team.

### 2.5 Hardware Sensor Prototypes

Students engaged in experiments with prototype sensors from the BBC and BEST labs and generated data for different sensing conditions and applications. Several projects involved sensor and circuit tuning and experiments and students collected data that was processed to detect events of interest for each project. Every hardware project had a well-defined application. Research projects for the REU are described in the next section.

## 3. RESEARCH PROJECTS

Nine research projects were overseen by faculty mentors in different labs. All projects had assigned faculty and graduate mentors. Students reported on their projects on a weekly basis to the REU directors. Projects are described below.

### 3.1 Signal Processing for Nanopore Sensors

Ion-channel and nanopore sensors [6] have several applications including DNA sequencing, detection of bio-threats, and water quality. Nanopore sensors produce very

small currents and binding events are often difficult to detect. In the REU project, the use of Wavelet analysis and synthesis for de-noising is explored as shown in Fig. 2. Selecting an appropriate wavelet basis was part of the study.

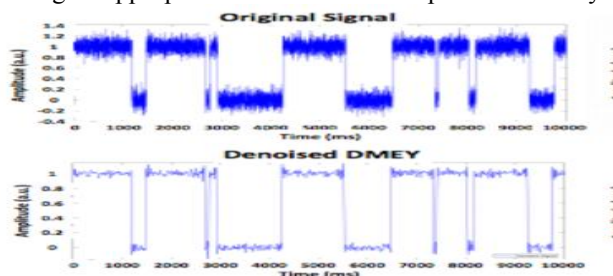


Fig. 2. The noisy and enhanced signal for a nanopore sensor.

### 3.2 Photoplethysmogram Sensor Arrays for the Detection of Early Signs of Cardiac Disease

Photoplethysmogram (PPG) sensor arrays are devices used to measure the volume of blood flowing through vasculature. The device uses OLEDs (Fig. 3) to emit light into the skin and then captures the data non-invasively. Using inexpensive flat panel screens bonded to a flexible backing [7] the device can conform to anatomy. Data is classified using machine learning algorithms to detect age related cardiac disease.

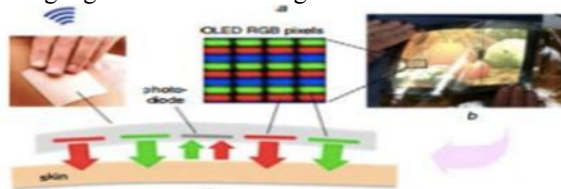


Fig. 3. PPG flexible display with OLED sensors.

### 3.3 Development of a CO<sub>2</sub> Analyzer

The development of a CO<sub>2</sub> analyzer is studied for health monitoring including diagnostics of diseases such as cardiovascular disease and asthma. The device consists of colorimetric sensing technology [8]. The system involves breathing into a flow tube and a sensor produces a signal displayed in a smartphone application that includes signal and data analysis algorithms for health diagnostics.

### 3.4 Fluorescent-based Lateral Flow Point of Care Detection of Cervical Cancer Biomarkers in Serum

Point-of-care (POC) diagnostics [9] provide low cost methods of disease detection in low resource settings.



Fig. 4. Point of Care Sensor Device [33,39].

The current platform detects antibodies in serum to recombinant protein biomarkers. POC tests use nitrocellulose lateral flow test with colorimetric detection.

Nitrocellulose enables fluid handling, serum filtration, better protein immobilization, rapid detection time, and affordability. We use fluorescent-based detection (Fig. 4) in a nitrocellulose lateral flow format to achieve higher sensitivity and semi-quantitative results to detect cervical cancer biomarkers.

### 3.5 Activity Detection via Sensor Fusion

In this REU project, an intuitive method for optimizing exercise routine data (Fig. 5) and providing feedback for future workout routines [10,35] is presented. This method utilizes microcontrollers with embedded sensors for activity detection. Additionally, this method also incorporates supervised and unsupervised learning algorithms, including multi-class Gaussian Support Vector Machine (SVM) [1] and K-Means clustering, to generate mobile phone predictive models for exercise routines.

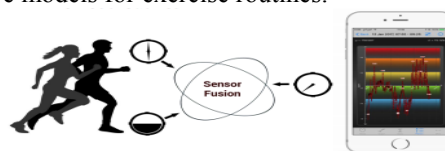


Fig. 5. Sensor fusion for mobile activity detection.

### 3.6 Crowd Sourced Environmental Monitoring

The goal of this project [11] is for respiratory disease patients to use wearable devices and monitor their condition relative to environmental parameters. These include temperature, ozone, and particulates. Inexpensive sensors are used to collect data and sensors improve reliability. The project seeks to explore methods to gather outdoor temporal data and relate them to respiratory effects.

### 3.7 Managing Respiratory Disease with Wearable Devices

Pollutants such as dust particles and ozone are known to distress patients with respiratory disease. Currently the one pollutant map available gives only a single value for the entire greater Phoenix area. The goal of this REU project is to develop wearable devices from small, inexpensive microprocessors and sensors [31,40] that will measure pollutants. The signal/data analysis tasks are to compile real time data and create a publically available pollutant map.

### 3.8 Monitoring Childhood Asthma

Asthma is the leading chronic childhood disease that affects seven million children in the United States. Currently, there is no simple scientific method of continuous monitoring of physiological or environmental conditions of asthma patients. The purpose of project is to create a wearable device [12] to connect human patients and the environment. This will be done by creating a Human-in-the-loop Cyber Physical System. COTS-sensors were used to create a pilot device. The data collected by the device enables correlation of symptoms with environmental markers.

### 3.9 Human Factors in Mobile Health Applications

Efficiently analyzing quality of air data can provide information to help parents with children suffering from asthma. The idea is to reduce the likelihood of a serious



attack. In this project, we explore formats to present a live “air-care” pollution map. The information is used to design the graphical user interface for a Human-in-the-Loop Cyber-Physical System that combines environmental data with physiological monitoring to improve patient understanding of health risks and likelihood of asthma attacks.

#### 4. DSP ALGORITHM AND SOFTWARE MODULES

Modules in Signal Processing and Machine Learning were developed. These included formal video streamed lectures in signal processing describing filters, spectra and statistical signal analysis. These lectures were accompanied by hands on programming exercise sessions. For software we used our own J-DSP [13,14,22] and several examples in MATLAB including exercises in noise removal using adaptive frequency domain filters [23]. Students were also introduced to parametric spectral estimators and linear prediction [16]. Machine learning and deep learning [1][27-30][32][34] was also introduced starting with feature extraction and principal components and descriptions of the k-means algorithm. Students examined the compaction properties of principal components using MATLAB experiments [15,20,26] and then looked at training and classification software. The new HTML 5 version of J-DSP [15,22,25] was also used for machine learning simulations (Fig. 6) and helped students understand quickly some of the clustering concepts. External assessments [41] showed that the combination of structured modules and research project experiences in labs proved to be very useful.

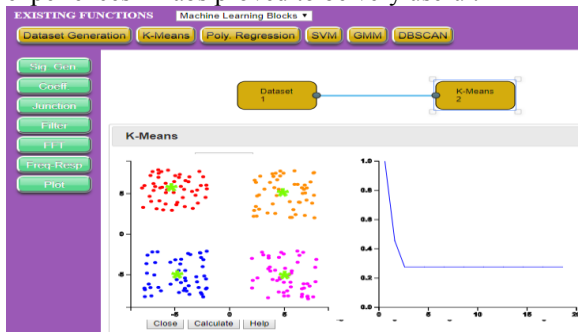


Fig. 6. Machine learning experiments using HTML5 J-DSP.

#### 5. SENSOR AND CIRCUIT MODULES

Modules in sensors were developed to help students understand the role that sensors play in assessing real-world data. There was a focus on the types of data, specifications, and parameters that sensors provide. In addition, sources of inaccuracies and noise were discussed. The modules were intended to teach students about the basics of sensors and front-end readout as well as providing a perspective on the data so they would understand what type of algorithms could be used to interpret the information.

#### 6. ASSESSMENTS

In our attempt to train students and assess the REU program we drew theory and lessons learned from several studies [17-40] as well as the NSF REU site resources [29]. Several

assessments were documented in the first year of the REU [41]. These consisted of assessing the effectiveness of the modules and the effectiveness of the overall research experience. Pre- and Post-quizzes and interviews were conducted. The research experience was analyzed in terms of Problem Solving and Communication, creativity, Collaboration, Research practices and crosscutting experiences. We show below a graph (Fig. 7) of pre- and post-quizzes on problem solving and communication.

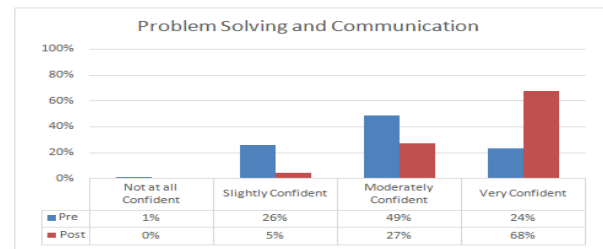


Fig. 7. Pre- and Post Assessment of Problem Solving [41].

When confidence was examined from pre to post-test, there was a significant increase in confidence levels ( $p < .001$ ).

#### 7. CONCLUSION

An REU program was launched at ASU with nine students entering in the first year. Nine distinct undergraduate research projects were launched in various research labs. In addition, several modules were prepared and delivered either via video streaming technology or face-to-face presentations. The experience was integrative in that it included both hardware and software experiences. Cross cutting modules also helped students become aware of ethics, standards, paper and patent preparation. Weekly presentations with feedback helped the students improve their communication skills. Poster sessions with industry in an I/UCRC meeting (Fig. 8) provided valuable feedback for all projects. Some REU projects were presented in conferences [31,33,35]. External REU assessments were very encouraging [41].



Fig. 8. a) REU students at the SenSIP industry meeting; b) students presenting sensor and DSP posters to industry.

#### 8. ACKNOWLEDGEMENTS

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