IRES Program in Sensors and Machine Learning for Energy Systems

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The international research experiences for students (IRES) program addresses multidisciplinary research at the overlap of sustainability, power systems, and signal processing with the aim of improving efficiency in PV power generation. The IRES program engages faculty at the ASU SenSIP Center and at the University of Cyprus' (UCy) KIOS Center to address fault detection and other research problems in solar energy arrays. IRES participants are tasked with studying algorithms and software to monitor and control solar arrays. Research involves using data from programmable sensors embedded in smart monitoring devices (SMDs) that are attached to solar panels. The SMDs have sensors, actuators and radios that enable researchers to work with a solar array where every panel provides data. IRES participants are trained to use machine learning to assess the solar array condition. The program also trains the students to perform research and present results in international settings. In the first year of the project, four students travelled to the University of Cyprus and worked with UCy faculty on fault detection. The program included weekly research presentations by the students at UCy, presentations at a local workshop and continued engagement after the summer experience at ASU. Two of the students were able to present and publish their work in international conferences.

Index terms – solar energy, machine learning, fault detection, radial basis networks, IRES.

I. INTRODUCTION

This paper describes an international program providing student research experiences in sensors and machine learning (ML) for energy systems. This three year international research experiences for students (IRES) site involves the Sensor Signal and Information Processing (SenSIP) center at Arizona State University (ASU) and the KIOS center at the University of Cyprus (UCy). The IRES program trains four to six students per year during the summers for up to eight weeks. The program embeds students in multidisciplinary research at the overlap of sustainability, power systems, and ML with the aim to advance the state of the art in solar monitoring and control. The project launches international collaboration with research projects under the auspices of the SenSIP and the KIOS centers. In the first year (summer 2019), four students travelled to Cyprus and worked with faculty mentors at ASU and UCy on fault detection [1-4], energy and load forecasting [5-7] and communication issues [8] in solar energy. IRES students were pre-trained at ASU in ML and signal processing and then traveled to UCy. At UCy, IRES students worked with faculty and graduate students in the research facilities of the KIOS center. Communications with ASU mentors while at UCy were maintained through frequent teleconferences. The program included structured video-streamed sessions, hands-on ML programming, and face-to-face lecture modules that provided training in ML for energy systems. The IRES participants also had training modules in crosscutting areas including culture, ethics, patent development, policies and standards. The first year experience was assessed by ASU's
College Research and Evaluation Services Team (CREST).

IRES objectives are to: a) introduce students to general research practices in international settings; b) engage students in research associated with solar monitoring and control; c) motivate IRES students to innovate and pursue research careers; d) train students to present their research to international stakeholders; and e) build awareness on international policies and standards.

IRES Student Participants

One of the goals of the IRES site is to recruit, train, and motivate students to pursue global research careers. We targeted recruitment of students from several STEM fields including Electrical Engineering, Computer Science, Mechanical Engineering, Physics, and Mathematics. A special effort was made to embrace diversity and inclusivity in our recruitment.

Intellectual Focus of the IRES Program

PV arrays encounter loss of efficiency under conditions of shading, panel faults, and temperature variations. In fact, shading, weather patterns, soiling and temperature reduce power output considerably. For example, a malfunction of one panel will cause an entire PV string to fail. ASU has produced a series of research results [2-4, 12-13, 17-19] for utility-scale Photovoltaic (PV) arrays and developed an experimental solar facility (Fig. 1) that consists of solar panels fitted with sensors and actuators to validate theoretical algorithms. The synergy with KIOS is based on complementary smart grid rooftop solar research and advanced inverter control at UCy that will help ASU develop and optimize algorithms, sensors, and communications for IoT networked rooftop systems.

Fig. 1. a) ASU Solar Monitoring facility [10]; b) the SMDs attached to panels; (c) SMD electronics, relays and radio.

To minimize inefficiencies, individual panel current-voltage (I-V) measurements, weather information [11], and imaging data [12] are essential. Controlling the power output is possible through solar panel matrix switching [18] and optimization (i.e., changing certain array connections from series to parallel using actuators). Matrix switching using programmable relays allows for different interconnection options. The research goal is to optimize PV array systems by: a) exploiting the measured I-V patterns to detect faults using ML, b) employing advanced imaging and vision techniques to predict shading, c) using temperature, irradiance and weather data to elevate PV efficiency, and d) include smart grid interfaces and networking considerations [14, 15]. A set of smart monitoring devices (SMDs) are connected to *each PV panel. SMDs* collect the individual panel metrics (current, voltage, irradiance, and temperature) periodically (about every 8 seconds) which can then be used to monitor and control the solar array. Cameras can also be installed to provide updates on cloud movement and shading at a rate of *20-30 frames per second*. The envisioned algorithmic and image/data analysis unit will be equipped with various state of the art algorithms for imaging, data mining and prediction that identify and track various important time-varying events and patterns. The algorithms will operate on PV measurements and on parametric models to detect and remedy faults using panel switching (Fig. 2).

The IRES project three year plan engages students in an international setting in the following research problems:

- How imaging is used to predict shading and elevate efficiency?
- How can array connections be reconfigured based on imaging, weather, and I-V data to optimize power?
- How can we detect and classify panel faults real time using ML?
- How do we extend utility-scale solar monitoring and control concepts to rooftop systems?
- How do we access data and program this *cyber physical* system in a cyber secure manner?

The overall concept controlling a solar energy system is shown in Figure 2. The SenSIP Center at ASU has developed a an 18kW testbed (Fig. 1) that has 104 panels - each panel fitted an SMD. The SMD monitors current, voltage, temperature, and irradiance and has wireless connectivity to a central hub. The SMDs enable connection topology reconfiguration which is guided by input on irradiance, shading, faults and an optimization algorithm.

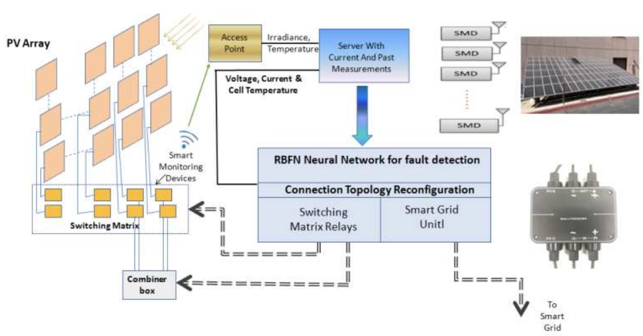

Fig. 2. Overview of the Solar Monitoring and Control System.

The rest of the paper is organized as follows. The IRES organization is summarized in *Section 2*. *Section 3* describes the student research projects in ML. It also describes the pre-training process using modules, lectures, and hands on ML experiences. *Section 4* explains the assessment, *Section 5* summarizes the IRES efforts starting in 2020, and *Section 6* presents concluding remarks.

II ORGANIZATION OF THE INTERNATIONAL PROGRAM

Undergraduate and graduate students applied for the program in the early spring of 2019 and recruited in late April. Two students have also been recruited in 2020. A diverse cohort of students were recruited in 2019 including two women, one of Hispanic origin, and one US Airforce veteran. In 2020, we recruited two students for a virtual experience due to the Covid-19 travel restrictions. Students completed pre-training in ML for PV array systems at ASU from mid-May to mid-June. The pre-training included modules and hands on software labs. IRES modules included: lab safety, introduction to research, signal processing, ML, and basics of PV systems. All the students prepared short proposals in scientific IEEE style format.

A. SenSIP and KIOS International Project Experience

Students chose a project in the area of the IRES program, and ASU and UCy mentors planned and monitored the tasks of each project. Each IRES student collaborated with a graduate student who was their immediate graduate mentor. IRES students were instructed to report their results in IEEE format to gain experience with publication formats and logistics. Students gave short weekly power point updates to the faculty and graduate mentors who provided feedback and further guidance. The students also planned a concept poster for presentation at the end of the summer. A final 4-page IEEE style formatted report was submitted by students. The students also presented their results in a culminating event and in a workshop in Cyprus [23]. The IRES directors, project mentors, and the evaluator provided feedback on the final reports and poster presentations.

B. Schedule of the International Research Experience

IRES students were immersed in designated ML and power systems project labs at ASU between May 15 and June 14 and at UCy later in June. Weekly tasks and milestones were established by the mentors. The challenge of integrative ML algorithm design for various PV system components was central to IRES projects. Students worked with their faculty and graduate mentor who guided them through solar data studies using ML tools from MATLAB and Python. Students reported their findings to their faculty and graduate advisors weekly. The program also included international collaborative sessions across ASU and UCy, weekly seminars, and post-seminar networking with faculty and other researchers.

C. Nature of IRES Student Activities

We adopted a strategy that had a) research modules (see Table below) and b) extensive hands-on computational projects in ML. The students spent time at ASU and UCy laboratories and received solar systems and ML training. Two of the students were involved with fault detection, one student became engaged with energy and load analytics, and one student addressed communications aspects of energy systems. All students learned how to use ML in their studies. The faculty advisor along with the PIs ensured research training and tasks were provided for each student.

Table Module and Research Schedule - Activities at ASU and KIOS

Week	Modules and Research	Task/Social	Activity
1 &2 ASU	**Pre-Travel A** Introduction to Protocols, Safety, Travel	Orientation /Meet ASU Mentors, Social.	General Overview of Projects and Deliverables
	Pre-Travel B - Cyprus Culture & Policy Pre-training	Attend Seminars / Read Materials	Videostreamed and live Lectures by Specialists.
	Pre-Travel C – Research in International Environments	Attend Seminars / Read Materials, Social	Videostreamed and live Lectures by Specialists.
3 Ucy	Signal Processing / ML Research Starts at KIOS	Meet Mentors at KIOS. Module, Social	Literature Review Project Research
4 Ucy	Research Continues in KIOS Labs	Project Proposal Update. Social.	Prepare 1 page project description IEEE style
5 Ucy	Research Continues in KIOS Labs	Presentation of Initial Research Result	Prepare Poster draft for local Workshop
6 Ucy	Research Continues in KIOS Labs	Patent Module Research Feedback	Participate in UCy workshop
7 Ucy	Research Continues in KIOS Labs	Cross cutting modules - Research Update	Presentation and Feedback by mentors
8 Ucy	Project presentation and poster at KIOS.	KIOS Final Meeting Presentation & Social	Research Ends Poster & Final Reviews
9 ASU	Arrive back at ASU	Debriefing / Social	Presentation at ASU

D. Approach to IRES Activities

Lessons learned from past engagement of the Co-PIs, faculty advisors, and graduate advisors in prior ASU and UCy programs helped establish tasks with outcomes for each student project. Students started with literature review on PV systems and ML and were encouraged to define research goals that would potentially lead to an archived publication. The advisors presented examples of prior successful REU and RET projects. One of the IRES goals is to sustain undergraduate interest in research after the international summer experience and motivate students to pursue research careers including global opportunities. The prospect of IRES students producing IP (patents) was enhanced by a seminar in patent development by Skysong Innovations. In addition to the research goals, IRES promoted professional development, cross cutting training in policies and ethics, and cultural training in Cyprus. IRES students visited historical and cultural sites, visited the US Embassy, and met with administrators including UCy department heads, the UCy rector, and the KIOS director. They also participated in SenSIP and KIOS research seminars.

E. Machine Learning Simulations and Experiments

The students were exposed to noise removal techniques, feature extraction, ML clustering, and regression algorithms for solar and energy datasets. Baseline examples were established for simulations, and several ML algorithms were compared in terms of PV fault classification performance.

F. PV System Analytics and Fault Clustering

Students engaged in simulating clustering and classification using solar data that was available from the ASU SenSIP site and from national databases. Student were exposed to the smart monitoring devices (SMDs) and on several occasions visited the SenSIP solar testbed [10] at the ASU research park where they attended demonstrations of SMDs. The two students that worked with fault detection ran and clustered data using K-means and neural network algorithms. They were then asked to test and classify various solar shading conditions using neural networks. One of the students worked with radial basis networks and developed new results that were archived on IEEE Explore [19]. The second undergraduate student collaborated with an REU student on load and energy analytics using ML [5,7] and the fourth student studied real-time wireless communications and also co-authored an IEEE submission [8]. All students gave presentations at the CWSPI workshop [23] in July 2019.

III. RESEARCH PROJECTS

Three research projects were advised by faculty and graduate mentors at ASU and UCy. Students reported progress on their projects on a weekly basis both face to face and via teleconferencing. Projects are described below.

A. Radial Basis Networks for Fault Detection

Interest and deployment of solar energy systems require effective and implementable fault detection strategies. Fault detection and shading effects have been previously studied for utility-scale PV arrays using various ML methods. Realistic synthetic data was created from a Simulink model and real data was obtained from the National Renewable Energy Laboratory (NREL) database [22] The NREL PVWatts Calculator [22] estimates the cost and amount of energy produced by the grid-connected photovoltaic energy systems throughout the world.

In this project, a Radial Basis Function Network (RFBN) approach to fault detection was explored. The RBFN was trained to cluster a variety of PV faults. The RBFN is a nonlinear neural network classifier that uses a radial basis activation functions in its hidden layers. It is a supervised learning algorithm and as such, each data point is passed through the network labeled with its true classification. In Figure 3, we show an architecture where each RBF neuron in the hidden layer(s) stores this training example. Each neuron takes the weighted sum of its input values and compares it to the training example.

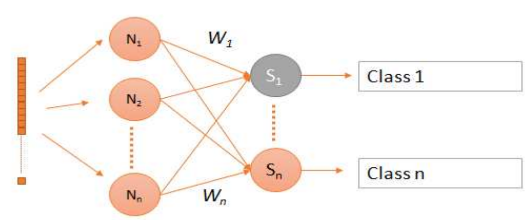

Fig. 3. Simplified RBFN Architecture used in IRES Project.

A confusion matrix was generated to assess performance of the RBFN. For noiseless data, the network identified fully shaded conditions with high accuracy. However, with typical noise levels due to high amperage and voltage variance, the accuracy dropped as expected. The results and confusion matrix were shown in [19]. Additional results for all neural network methods for solar monitoring can be found in [28].

B. Fault Detection for Rooftop Installations

Currently the production of rooftop solar power requires reliable fault detection to assess soiling and shading as well as other electrical faults. ML techniques can be used for rooftop systems using a variety of methods [13]. A database was made available at the UCy and data was examined and processed by ML algorithms. Initial results on clustering were reported in an IRES poster.

C. Anomaly Detection for Energy Load Analysis

Anomaly detection helps researchers determine analytics in energy usage. It also provides opportunities for energy and load forecasting which can help form strategies to avoid blackouts. ML algorithms and time series models can be used to detect periodicities and other correlation models. Several features have been examined and results reported in [5,7].

D. Communication Systems for Solar Monitoring

Many of the utility scale solar sites use cellular systems for monitoring and analytics. This project focused on ML for wireless communications and specifically real time implementations of MIMO (Multiple Input Multiple Output) systems which promise to increase capacity of next generation cellular networks. There is additional interest in DoD related applications for use in anti-jamming and other military communications tasks. To address these opportunities, the IRES project seeks to implement a real time MIMO software defined radio system (Fig. 4) to test ML algorithms in channel and frequency estimation.

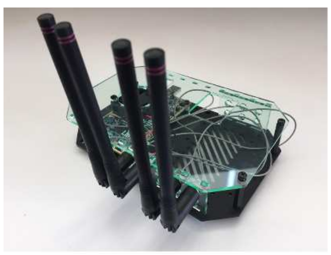

Fig. 4. The LimeSDR RF 2x2 MIMO transmitter and receiver [21].

IV. Assessment of the Program by CREST

The evaluation and assessment of the SenSIP IRES program focused on the following issues: a) knowledge gained by IRES students, b) recruitment and diversity, and c) experience gained in an international setting. The evaluation was completed by ASU's College Research and Evaluation Services Team (CREST). CREST conducted both formative and outcome assessment and analyzed the activities delivered, participation in activities, and participant satisfaction. Formative assessment used document review to confirm that activities were implemented and Principal Investigators and staff made data-driven decisions on program activities. In Figure 5, IRES participants reported on their confidence in research skills at the beginning and at the end of the program. Using a 4-point scale (1=not at all confident; 4=extremely confident), the chart shows the percentage of participants who reported moderate or extreme confidence in their research skills. While many participants started with moderate levels of confidence, by the end of the program, all participants reported high levels of confidence in their research skills.

Figure 5. Assessment of Research Skills gained in IRES.

V. The IRES Program in 2020

Two ASU students have been recruited in the 2020 IRES program which was carried on-line because of the COVID- 19 travel restrictions. The ASU students are advised by the PI of the project. Evaluation is being done by CREST. The students did not travel to the University of Cyprus but they teleconferenced with Cyprus mentors and students biweekly and began working on solar data provided by UCy. Both students are focused on applying a variety of ML algorithms including Positive Unlabelled learning [20] on PV fault detection and soiling for rooftop systems. More specifically, the IRES 2020 research focused on identifying soiled solar panels in need of cleaning and estimating the amount of energy loss due to soilage. This was performed using only the geographic solar array location (Figure 6) and five-minute energy output readings from the residential sites themselves. Techniques for weather compensation and PV array size, position, and angle normalization were developed for this never before used dataset provided by SolarEdge, a solar company in Cyprus. By having team members in Cyprus close the loop by confirming predicted results, the students were able to determine the effectiveness of their models.

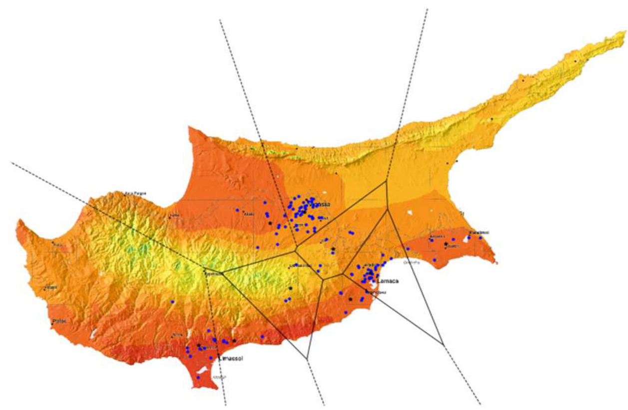

Fig. 6. Geographic solar array location and density in Cyprus.

Other activities include graph-based ML [17] and topology optimization [18]. In Cyprus, three faculty, one post doctoral fellow, and one graduate student are involved. Preliminary assessments of all activities are positive. The students will prepare collaborative reports and publications with UCy mentors. Research in the summer of 2021 will still focus on the customizing ML algorithms [29-38] for solar array performance optimization.

A. Access to Rooftop Solar System Database in Cyprus

The IRES participants have access to an online database, comprised of residential PV plants [15] in Cyprus. These are managed by Eletoyia Photovoltaics in Cyprus. The reporting rate of the PV plants is 5 minutes. The data includes the entire record of each PV plant from the time that it was installed and measurements from the DC side including real-time power generation, voltage, and current. It provides some grid (AC) related data such as the injected active and reactive power, the frequency [24,25], and the power factor of the plant.

B. Outreach Efforts

Outreach is planned through a new RET program [26, 27] which trains teachers in ML for PV systems. The effort brings faculty from the ASU Mary Lou Fulton Teachers college. Two teachers working with our SenSIP RET program have been provided with Cyprus data and begun running ML algorithms to detect soiling and other PV faults.

VI. Conclusion

This paper presented the activities and summarized some of the results of the IRES 2019 program. It also provided information on the beginning of the 2020 IRES program. The basic training effort, the schedule and the projects were briefly discussed. Two of the students participating in the IRES program have submitted papers to conferences and all the students have presented their results at the CWSPI 2019 [23] workshop in Cyprus. In addition to the scientific efforts at UCy, the students have held several visits and meetings to enrich their knowledge of culture and policies in an EU country. Their visits included: a) meeting with department heads, b) meeting the UCy rector, c) meeting US Embassy officers in Nicosia, d) site visit to a startup company on solar technologies, and e) visits to cultural and historical sites.

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