INTELLIGENT MECHATRONIC TECHNOLOGIES FOR GREEN ENERGY SYSTEMS

Shunmugham R. Pandian
Department of Computer Science & Industrial Technology
Southeastern Louisiana University
Hammond, LA 70402
spandian@selu.edu

Abstract

The field of renewable energy represents a new frontier for the academic and research community. This paper presents a survey of several emerging developments in the field of mechatronics education and research, with applications in the area of renewable energy systems. Educators have focused on the integration of fundamental concepts from theory courses on mechanical design, materials, dynamics, electronics, interfacing, machines, computer control, programming, and intelligent systems with laboratory experiments and project-based learning, especially for renewable energy systems such as solar, wind, and micro hydroelectric systems. The concepts can be utilized for area-specific experiments and laboratory courses at junior and senior levels, supervised and independent study courses, and senior capstone design projects. In addition to advancement of education and training in the frontier area of green energy, the focus on mechatronics education can also lead to new technologies and business ventures, training in unstructured problem solving and engineering design, and involvement of engineering and technology students in community service and outreach. The paper includes a discussion of the ongoing education and curricular development by the author in the area of mechatronics and renewable energy systems.

1. Introduction

Energy is the driving force of modern societies, and generation and utilization of energy are essential for socio-economic development. Per-capita energy consumption levels are often considered a good measure of a nation's prosperity. In recent years, energy scarcity has become a serious problem due to depletion of fossil fuel sources, increasing population particularly in resource-scarce developing countries, globalization of energy-intensive economic growth, environmental pollution, and anthropogenic Global Warming/climate changes [1]. As a result, the field of renewable energy represents a new frontier for the academic and research community.

While in developed countries the *energy problem* is one of short-term scarcity, higher prices, or conservation, an estimated 40% of the world's population – or, 2.5 billion people mainly in the less developed countries – do not have even have regular access to electricity. Moreover, this number is expected to double by the year 2050. The reasons for this limited access to electricity in developing countries are the lack of conventional energy sources such as coal, oil, or nuclear energy, low incomes whereby about 40 percent of the population has incomes of less than two dollars a day, and – even where energy sources exist – the lack of expensive capital to exploit available resources [2].

In the present day climate of global economic recession, looming effects of Global Warming, and disappearance of high-paying manufacturing jobs due to outsourcing and off-shoring of factories to low-wage countries, there has been a widespread recognition of the promise of *Green Energy Technologies*. These technologies are environment-friendly, renewable, and low-polluting. The major types of green energy sources are solar, wind, tidal/wave, geothermal, small-scale hydropower, and biomass. Generation, transmission, and utilization of green energy can help produce several hundreds of thousands of high-paying jobs that cannot be outsourced, and will play a major role in future policy schemes such as cap and trade or carbon tax designed to regulate the impact of polluting fossil fuel sources. Green energy technologies are guaranteed to be a major socio-economic force in the future, and will pose remarkable challenges and opportunities to academics and researchers on the one hand, and practicing engineers and technologists on the other.

2. Mechatronic Systems

Mechatronics is a modern, interdisciplinary field comprising mechanical systems, electronics, and computers, and has attracted much attention over the past decade [3-4]. Mechatronic systems are mechanical systems controlled by computer software with electronics hardware. In a sense, robotics may be considered a sub-discipline of mechatronics. Of course, mechatronics has previously been known by other names, such as industrial electronics, electromechanical systems engineering, etc. The new and popular term *mechatronics* captures the prevalence of computer control in erstwhile mostly mechanical systems.

Mechatronics lies at the heart of many of the outstanding technological achievements of the twentieth and early twenty-first centuries. The decreasing cost and size on the one hand, and increasing power and versatility on the other, of electrical machines, sensors, controllers, and computers have resulted in the incorporation of computer control methodology in many technological systems. Some examples are modern automobiles with enhanced safety, fuel efficiency, and comfort due to use of on-board computers, industrial automation, robots, consumer appliances, healthcare and assistive technologies, energy systems, environmental monitoring and control, and defense applications such as surveillance and missiles. Another good example of this development is the technology of hybrid cars and plug-in/electric *cars*. Similar trends of computer control impacting traditional systems can be observed in other fields, such as avionics and bionics, pneumatic technology becoming electropneumatics, hydraulic systems transformed to electrohydraulic systems, and so on. Incorporation of computer control results in increased economic competitiveness due to *innovation* and *value added* in terms of energy efficiency, safety, comfort, novelty, and environment-friendliness.

Thus, mechatronics (and robotics, as special cases of mechatronics) has become a major frontier of engineering and technology, with wide-ranging applications in a variety of disciplines. Some of the most outstanding technological achievements of recent years, e.g., Mars Rover, Space Shuttles, hybrid/fuel-cell cars, micro- and nano-electromechanical systems, unmanned aerial vehicles, artificial heart, and Segway personal transporter, to name just a few, are all good examples of mechatronic systems.

The applications of mechatronics have become central to the study of mechanical, electrical, and computer science and engineering disciplines. In recent years there has been a tremendous growth in their applications to practical systems, in other engineering disciplines: e.g., agricultural engineering (heavy equipment control), civil engineering (intelligent buildings and transportation systems), chemical engineering (intelligent process control), environmental engineering (monitoring and control), and biomedical engineering (microelectromechanical systems and assistive technologies).

The next stage in the evolution of computer controlled systems are the *intelligent mechatronic systems*, which combine the power of computer control with software for incorporating intelligence through artificial/computational intelligence techniques [5-6]. The resulting systems have several advantages such as human-like learning and adaptation capability, safety (e.g., adaptive cruise control of automobiles), energy efficiency (e.g., intelligent engine control, smart wind turbines), convenience (e.g., telematics for cars), and hazard-avoidance for humans (e.g., autonomous vehicles/aircraft/gliders for the battlefield, autonomous robots for mines). In more sophisticated cases, multiple mechatronic systems with *embedded* intelligent agents may cooperate through communication networks, e.g. [7].

This paper explores avenues for contributions by engineering and technology educators to the development of green energy technologies through innovative education in mechatronics. The basic aspects of mechatronic systems and their importance are highlighted first. The analysis and design of key renewable energy systems, viz., for wind, solar, and micro hydroelectric power generation, as mechatronic systems are discussed next. A template for theoretical and laboratory hands-on instruction in intelligent mechatronic systems for green energy is presented. The paper concludes with a discussion of the education and curricular development by the author and his students in the area of mechatronics and renewable energy systems.

3. Intelligent Mechatronic Systems for Green Energy Technologies

A majority of the renewable, green energy technologies involve electromechanical energy conversion. For example, in wind, tidal, wave, hydroelectric and human power conversion systems, kinetic or potential energy is converted into electric energy through an electromagnetic generator. Many solar energy systems directly generate electricity from light (e.g., photovoltaic), but incorporate extensive use of electronics and computer control for efficient power conversion, regulation, and storage. Other types of renewable energy systems like solar thermal and geothermal systems involve indirect use of electromechanical systems such as steam turbines and generators.

Intelligent or autonomous systems techniques have been well studied from the viewpoints of artificial intelligence and biologically-inspired computational intelligence techniques, as well as *hybrid* methods which combine the power of both approaches [8]. They have been widely applied in a variety of fields, and in robotics and mechatronics for tasks such as planning, sensor fusion, control, and cognition. Many of these techniques are recently being applied widely to power systems based on conventional energy technologies such as nuclear, hydrothermal, and hydroelectric, e.g., [9].

Mechatronic systems are central to the study of various green energy systems. Traditionally, mechatronics education and research focus on the dynamics and control of systems in motion, such as motors and robots which convert electrical energy into mechanical energy. By contrast, renewable energy systems such as wind and tidal energy systems are centered on the use of generators to convert mechanical energy into electrical energy (motors operated in reverse, possibly with special design considerations for high efficiency). Therefore, it is fairly straightforward to extend the scope of mechatronic systems studies to applications in green energy technologies.

Given the similarities of renewable energy systems with robots and mechatronic systems on the one hand, and with conventional energy systems on the other, researchers have in recent years turned to application of intelligent systems techniques to improve the performance of green energy systems and *smart grids*. In particular, problems of design and optimization, modeling and system identification, control, and forecasting have been studied using the techniques of expert systems, fuzzy logic, artificial neural networks, and genetic algorithms.

As an example of the use of computational intelligence techniques in design, Kalogirou, et al have applied an artificial neural network for modeling of solar water heating systems of different designs under variable weather conditions. The network is used to predict fairly accurately the energy output from the heating systems, with advantages of speed and simplicity [10]. This technique was later extended to the optimal design of solar energy systems using a genetic algorithm for the purpose of maximizing lifecycle savings under variable parameters such as collector area, volume, mass flow rate, and so on [11]. Similar applications of identification methods to wind energy systems have been made, e.g., [12].

Similar to their use in advanced motion control systems, both conventional and intelligent control methods have been applied to renewable energy systems. As in industrial control systems, commercial wind energy systems are still mainly controlled using decentralized, single-input, single-output controllers [13]. However, the potential for benefits from the application of multiple-input, multiple-output, nonlinear, adaptive, and intelligent control methods in this area is significant, e.g., [14].

A major challenge in the design, development, and operation of renewable energy systems is the uncertainties imposed by environmental variables such as light, temperature, wind, water flow, and so on. Therefore, issues of power quality and stability are important factors to be considered in the design and control stages. The availability of low-cost microcontrollers enables the application of advanced control methods to decentralized or distributed renewable energy systems. In [15], Pandiaraj, et al have applied a microcontroller-based implementation of a fuzzy control system for intelligent load switching in the case of a micro-hydro system.

The innovative R&D work performed in the field of renewable energy systems has accompanied rising interest among the public in general, and university faculty and students in particular, about the exciting challenges posed in the study of green energy technologies. However, much work needs to be done on educating undergraduate STEM (science, technology, engineering, and math) students in the renewable energy systems field.

4. Active Learning in Engineering and Technology Education

The current revolutionary, rather than evolutionary, changes in the engineering technology education accreditation criteria by the ABET show that acquisition of technical knowledge alone is not sufficient for graduating engineers and technologists in today's globalized workplace [16]. The students also need training and experience in the areas of technical communication, ethics, team work, economics and ergonomics of system/product design, awareness of relationship between technology and society, civic engagement, sensitivity to cultural diversity, and so on.

In recent years, universities have emphasized innovative approaches to engineering and technology education, known as *hands-on learning*, *learning by/while doing*, *problem-based learning*, and *project-based learning* [17-18].The benefits of such student-centered, *active learning* approaches are most readily gained through practical laboratory and project-based instruction. The learning methods can be implemented in various contexts: e.g., problem solving in a single course, multiple case studies, mini-projects, and major projects.

Machines in general and robots in particular, have strong appeal to the *playful learning* dimension of children and youth. Therefore, class and group projects in the fields of robotics and mechatronics have been used to enhance student learning and understanding of materials learned in theory courses, e.g., [19]. Such projects typically also have the benefit of sustaining student interest and motivation, thereby improving retention [20]. In the process, the students are introduced to real-world multidisciplinary problem solving experiences in an unstructured environment. The group projects further provide them with valuable experience in teamwork, written and oral communication, time management, engineering economics, and understanding of technology's relation to society.

5. Engineering and Technology Education in Green Energy

Despite the high levels of popular and technical interest in green energy technologies, educational endeavors in this area are still not widespread. Historically, electrical and mechanical engineers have been introduced to renewable energy systems through parts of undergraduate courses such as energy conversion, electrical machines, and power systems.

Many of the early new programs in renewable energy were understandably at the graduate level, e.g., [21]. In the 1980s, the Center for Energy Studies at the Indian Institute of Technology, Delhi was founded as an interdisciplinary center for graduate education and research in conventional and renewable energy systems [22]. It also offered short-term training courses to engineers and technicians from developing countries in Asia and Africa in the areas of solar and biomass energy. The European Solar Engineering School was formed in 1996 offering a one-year masters program in solar energy engineering [23].

More recently, undergraduate students of engineering and technology are being introduced to green energy systems at the level of project-based learning, e.g., [24]. Only recently, full-fledged undergraduate programs in renewable energy systems are being introduced in U.S. universities, starting with the Oregon Institute of Technology in 2005 which offers a bachelor's degree in Renewable Energy Engineering [25]. In 2008, a concentration in Energy Engineering Technology with emphasis on green energy systems has been introduced as part of a new B.S. in Engineering Technology (ET, hereafter) program at Southeastern Louisiana University (SELU) in the Computer Science and Industrial Technology (CS&IT) Department.

The main difference between the engineering and technology curricula for energy education lies in the fact that the former focuses more on analysis and design using higher mathematics-intensive courses, whereas the latter concentrates on applications and systems integration with an emphasis on laboratory-based learning.

Specialized degree programs in energy systems rely on education on many of the core engineering courses offered to electrical and mechanical engineering and technology courses:

- *Core areas:*
    - Technical/Engineering mathematics
    - Computer programming
    - Engineering economics

- *Electrical:*
    - DC, AC, and polyphase circuits
    - Analog and digital electronics
    - Power electronics
    - Electric machines
    - Control systems
    - Power systems

- *Mechanical :*
    - Statics
    - Dynamics
    - Materials and manufacturing processes
    - Thermodynamics and heat transfer
    - Fluid mechanics

Major specialized courses related to energy systems may include

- Photovoltaic systems
- Solar thermal systems
- Wind energy systems
- Hydroelectric energy systems
- Nuclear energy systems
- Biofuel and biomass systems

In addition, students will have the option of taking elective courses in areas such as HVAC, Energy-efficient construction, Geothermal energy systems, Instrumentation systems, and so on.

Finally, a two-semester sequence of the Senior Project course is a major part of the curriculum in energy education. The projects will be team-based and involve integration and application of key concepts learned in the core and specialized courses for real-world problem solving.

6. A Mechatronics Laboratory for Green Energy Technologies

The author is currently involved in the development of an intelligent systems laboratory focusing on robotic and mechatronics, in the CS&IT Department at Southeastern Louisiana University for use by undergraduate and graduate students of engineering technology and computer science. Using many of the existing facilities of the lab such as motors, generators, data acquisition boards, servo amplifiers, test and measuring equipment, as well as software tools, it is also planned to develop experimental modules in renewable energy systems for use in laboratory courses for the new Energy Engineering Technology (EET) concentration majors. The facilities will further be available for use by other ET majors (especially, computer, construction, and mechanical ET concentrations) and Computer Science majors for senior capstone projects and for Supervised/Independent Study courses under faculty supervision.

The *specific aims* and related *activities* of the green energy technology component of the new Mechatronics Laboratory are:

(1) Development of undergraduate laboratory modules focusing on hands-on mechatronic experimental modules in solar, wind, and micro hydropower systems,

Activities: Acquisition of hardware and associated software necessary to set up undergraduate laboratory experiments in green energy systems for junior and senior ET majors.

(2) Integration of fundamental concepts from theory courses on mechanical design, materials, dynamics, interfacing, electronics, machines, control, and programming with practical laboratory applications,

Activities: Conceptualization, design, construction, implementation, and testing of experimental modules to conduct the lab experiments in individual lab courses.

(3) Introduction of undergraduate students to *practical applications* of intelligent systems concepts for renewable energy systems,

Activities: Use of interface cards for data acquisition, and C language programming on PCs and Arduino, Basic Stamp, and PIC microcontrollers. Incorporation of software-based demo modules of intelligent systems: e.g., based on Matlab toolboxes (fuzzy logic, neural networks, and genetic algorithms), Real-Time Workshop for code generation, use of Matlab/Simulink for modeling and simulation, NI LabVIEW for sensor feedback and GUI design.

(4) Facilitating the use of the new facility for senior capstone design projects, supervised and independent study courses, and faculty-student research.

Activities: Maintenance, security, upgrading of infrastructure, and project work by undergraduate and graduate students under faculty supervision.

(5) Formative and summative evaluation of the project work, assessment of student learning outcomes, and dissemination of project knowledge base.
Activities: Networking with faculty colleagues and STEM education community members, and soliciting student input on project design in the formative stages, during implementation, and at the conclusion.

(6) Community service and outreach efforts in publicizing green energy technologies using the laboratory systems.
Activities: Facilitating service learning using the new infrastructure, community outreach with local schools and community partners, collaboration with university administration on campus-wide green technology initiatives, assistance to student groups such as Green Club, and mentoring of student participants in design competitions.

As the EET concentration is being started new at SELU, for the renewable energy courses offered in the program it is planned to begin with two lab courses at the junior and senior level:

(i) Energy Systems Lab I (junior): *experiments* in photovoltaic systems, solar thermal systems, and wind energy conversion

(ii) Energy Systems Lab II (senior): *experiments* in intelligent control of energy systems, and energy-efficient systems, and *mini-projects* on photovoltaic systems, solar thermal systems, wind energy conversion, and energy-efficient systems

For the junior lab, the experimental systems to be implemented will be selected from the list of *suggested experiments* below:

(1) Basic measurements and instrumentation methods – power, wind speed, and solar energy measurements, common sensors used in energy systems, PC- and microcontroller-based data acquisition and data logging, graphing and visualization of data, GUI design for monitoring, use of NI LabVIEW
(2) Experiments in real-time control - programming in C/C++ for analog/digital control, microcontroller- and PLC-based control systems
(3) Basic experiment on photovoltaic energy conversion – use of different types of solar panels (viz., monocrystalline, polycrystalline, and amorphous), comparison of efficiencies, voltage and current regulation circuits for typical applications (e.g., LED lighting, small motors, and water pumps) and battery storage [26-27]
(4) I-V (current-voltage) and power control characteristics of photovoltaic panels – power control, maximum powerpoint tracking control, smart DC-DC converters [28]
(5) Experiment on solar thermal power conversion – solar heating system, temperature monitoring and control system [29]
(6) Basic experiments on wind energy conversion – measurements, instrumentation, and data logging with a small wind turbine, power control [30]
(7) Experiments on actuators as energy converters – electric (AC/DC), pneumatic, and hydraulic actuators [31]

For the senior lab, the experimental facilities will be developed to facilitate student work on the list of *suggested projects* below:

(1) Microcontroller-based systems for photovoltaic energy conversion – analog/digital interfacing, C programming, suggested use with Basic Stamp, PIC, AVR, or Arduino microcontrollers [32]
(2) Microcontroller-based system for small wind turbine power generation [33]
(3) Intelligent systems for renewable energy – modeling and simulations based on of Matlab/ Simulink/toolboxes/Real-Time Workshop and fuzzy/neural network/genetic algorithm methods
(4) Energy-efficient motion control techniques for actuators (electric, hydraulic, and pneumatic)
(5) Passive solar building – construction and monitoring [34]
(6) *Off-campus* work on small hydropower generation systems [35]

In the case of applications of real-time intelligent system techniques for green energy technologies, there are time, skills, and effort constraints on undergraduate students of engineering technology and computer science in development of real-time software and implementation of intelligent control algorithms. Therefore, *demo* programs with user interfaces will have already been developed for basic computational intelligence techniques such fuzzy logic, neural networks, and genetic algorithms. The students will then be required simply to apply various methods for different choices of design parameters (e.g., fuzzy membership functions and control rules, number of hidden layers and neurons in a neural network, mutation parameters in a genetic algorithm), e.g., [36]. The subsequent results for simulation models or actual physical systems will be displayed, and the students will be expected to perform physical interpretation of the results. Software for renewable energy systems such as Polysun 4 for solar thermal systems will also be introduced for student use.

The implementation of intelligent systems methodologies in the above manner obviates the need for undergraduate students to be involved in the demanding tasks of coding intelligent systems algorithms, but nevertheless provides them with experiences of intelligent systems performance with reference to key measures such as cost, efficiency, and quality. Students who wish to develop their own intelligent systems software for project purposes can use the laboratory code and modify it to fit their needs.

At the University of Michigan-Flint, Tulane University, and currently at SELU, the author has supervised undergraduate students on projects related to renewable energy systems [19]. One of the senior capstone design projects was on low-cost micro hydroelectric power generation from the Flint River. Another project was a freshman class project on a mobile robot with a solar panel for recharging the on-board batteries. A third project was done by two seniors in collaboration with Sloan Museum, Flint, MI as a microcontroller-based hands-on demonstration module for thermal-electric energy conversion. As such, these projects exemplify the use of engineering projects in community service, or EPICS [37].

During 2004-05, the author served as a faculty advisor to the Green Club of students at Tulane University. Several undergraduate and graduate students participated in the Environmental

Protection Agency's *P3: People, Prosperity and the Planet Student Design Competition for Sustainability*. They proposed the use of micro hydroelectric power generation from the Mississippi River in New Orleans, using underwater turbines. The team was awarded a $10,000 preliminary grant to work on a prototype of the proposed project "Renewable energy for the Riversphere".

7. Learning in the Real World

Unlike in the case of conventional energy systems, the use of green energy sources is severely constrained by socio-economic, environmental, and geographic factors. Therefore, in addition to learning in the class room and laboratory environments, the students will be encouraged to be open to real-world learning opportunities. This will enable the students to select challenging and rewarding open-ended, unstructured problems with real world relevance and commercial potential for their projects. Given the demand from the public and private sectors for renewable energy supplies, it is possible that some of the student projects facilitated by the proposed grant work could lead to new business ventures.

Additionally, the new laboratory infrastructure will be used to encourage student participation in regional and national design contests for university students, such as

(i) DARPA Wearable Power Competition (www.dod.mil/ddre/prize/topic.html),
(ii) Human powered submarine competition (http://www.isrsubrace.org/),
(iii) American Solar Challenge solar powered car race (http://www.americansolarchallenge.org/), and
(iv) EPA *P3: People, Prosperity and the Planet Student Design Competition for Sustainability* (http://www.epa.gov/P3/)
(v) Formula SAE student car design contest (http://students.sae.org/competitions/formulaseries/)

Participation in such design competitions would provide students the benefits of professional development, teamwork, timeline-bound problem solving within real world constraints, and innovative thinking skills [38].

8. Conclusions

This paper has presented an overview of the potential for mechatronics-based education in the area of green energy technologies. Many established engineering and technology education programs already have substantial laboratory infrastructure for use with courses such as control systems, robotics, mechatronics, and senior projects. With the addition of fairly inexpensive basic renewable energy components and systems such as photovoltaic solar panels, small wind turbines, fuel cells, etc, these facilities can be used for providing a strong theoretical and practical foundation in the vital area of renewable energy systems. Moreover, with the maturing of the field of intelligent and autonomous systems and its applications to areas such as robotics, mechatronics, controls, and power systems, a start can be made in introducing undergraduate students to education in the methodology of intelligent mechatronic systems for applications in green energy technologies.

Acknowledgements

The author would like to thank the Louisiana Board of Regents for an Undergraduate Enhancement Grant for the project entitled "Development of a Mechatronics Laboratory for Engineering Technologies", and the Office of Technology of Southeastern Louisiana University for a Student Tech Fee Grant for the project entitled "Hands-on projects in renewable energy systems for engineering technologies".

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