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Using Solar Energy in Robotics and Small Scale Electronic Applications

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Abstract

Now, more than ever before, the use of renewable energy is critical to the well being of our planet. Solar energy, in particular, is one of the main sources of renewable energy and the subject of research worldwide. While most renewable energy projects using solar energy target large-scale applications, renewable energy technologies are also suited for small-scale applications. This is evident in hand held calculators, recreation electronics and more recently, in traffic signals. One of the main issues encountered in the renewable energy industry, particularly the solar energy arena, is the storage of the harvested energy. The conventional method is by using batteries. Batteries however, present limitations and are not feasible for certain application due the high internal resistance and the bulkiness created by the need to combine them to achieve higher power capabilities. This adds to the efficiency limitation that still exists in the current photovoltaic industry. Researchers around the world have been making great progress to increase the feasibility of the solar power industry from both stand points. One of the areas that have been gaining traction is the introduction of other forms of energy storage.

This paper presents a novel approach to the storage of solar energy for applications where weight may be a constraint. Particularly, we exploit the use of supercapacitors as an alternative storage method for robotics and small scale electronics. To this end, a solar powered robot was designed and tests were conducted indoor using high power light sources.

Introduction

The continuous discovery of novel materials used to fabricate the harvesting cells sustains the ambition of increased efficiency and the possibility of arriving to a global energy solution based on solar energy. However, solar energy is far from replacing conventional forms of energy used to supply the growing public and commercial demand. The highest market efficiency is about 24.2% and made available at a very high cost to the consumer. Incentives offered by states and the federal government encouraging residents to use alternative sources of renewable energy are having a negative effect on the solar industry by increasing demand and thus increasing the price to obtain the technology, especially in the private sector [1].

Exploring alternate sources of energy has become a priority amongst the scientific community. Recent oil spills, mine disasters, and global warming have been the driving forces behind this ever growing interest in alternative sources of energy throughout the world. Solar energy, in many ways, seems to be the obvious solution to the soon to be a global energy crisis. The conversion of solar radiation into usable energy is still very expensive and inefficient. One of the problems is the power efficiency of materials used for fabrication of photovoltaic cells (PV). Storage of the harvested energy from the sun can also present an issue, due to losses and further processing such as conversion from DC to AC. For some applications, the energy is transferred directly to a grid system. In others, batteries are used to hold the converted energy. In very small scale applications, a capacitor connected to a solar engine maintains the voltage at nearly constant level. For applications requiring higher energy and relatively light weight, this technique will not hold and the need for alternatives must be investigated.

This paper presents the results of a capstone project in Electronic Engineering Technology aimed to investigate an alternative way of storing solar energy for robotics and small scale, light weight applications. First, the background information necessary to understand the technology used for the design is presented followed by a detailed design description of a solar robot used to investigate the feasibility of the project.

Photovoltaic Cells

The photovoltaic effect was first discovered by a French physicist, Edmund Becquerel, while experimenting with an electrolytic cell made up of two metal electrodes. He observed that exposing the metals to sun light caused an increase in conductance. Nearly forty years later, a structure considered to be the first solar cell, with about 1% efficiency, was developed. It wasn't until semiconductor materials were discovered that more efficient photovoltaic cells, using p-n junctions, were introduced. The efficiency of a cell is mainly a function of fabrication material, the junction, and the electrical contacts [2].

The ideal material must exhibit the ''photovoltaic effect", which is the ability to absorb and convert sunlight into electricity. Sun radiation consists of energy packets called photons. These photons have an energy related to their frequency ($E_p = hf = hc/\lambda \geq E_g$) [2] and thus wavelengths. For a material to be used in PV cell fabrication it must be able to absorb these photons. In semiconductor materials, electrons reside in discrete energy levels, mainly in the conduction and valence bands. The separation between these bands is called the band gap and the energy required to overcome the band gap is known as the band gap energy. Once an electron overcomes the band gap energy, it is free to move about the semiconductor. If a closed circuit is formed with the bulk, an electrical current is generated. Semiconductors have a relatively small band gap making them ideal for PV cells applications. Semiconductor materials that are commonly used for photovoltaic fabrication are mostly silicon based. They include monocrystalline silicon, polycrystalline silicone and thin films. When a positively charged semiconductor (p-type) is brought in contact with a negatively charged semiconductor (n-type) a p-n junction is formed and a region of high electrical field is created at the interface (free of electrons or holes). This is known as the depletion region [2].

When light hits the surface of a semiconductor, energy is absorbed from the photons, knocking off the bond between electron and holes and generating excess electron-hole pairs (EHPs) in the semiconductor. In general, EHPs generated within a diffusion length of a junction depletion region will be swept into the region contributing to the photocurrent (I_{PH}) [2]. Figure 1 depicts a common p-n junction diode. If an external bias is applied to the diode, then it is called a photodiode and it operates in reverse bias. The total current in this case is given by equation 1 [2]. When there is no external bias the diode operated as a photovoltaic cell as illustrated in Figure 2.

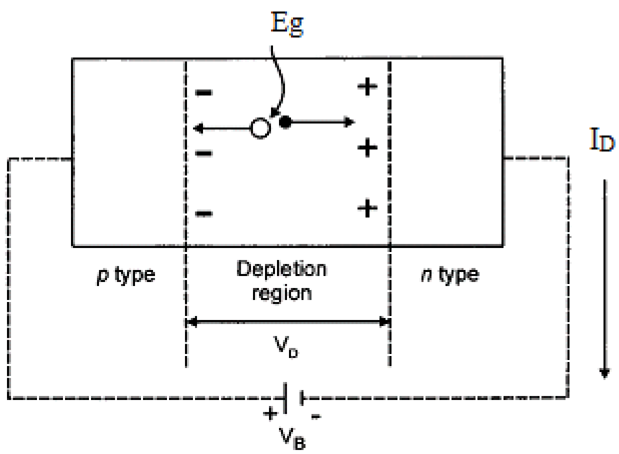

Figure 1: A p-n junction structure

The depletion width of a photodiode increases when a reverse biasing voltage is applied to the terminals of the device. The reverse bias diode current is given by [2],

$$I_D = -I_S - I_{PH} \qquad [A] \tag{1}$$

where, I_S is the reverse saturation current and I_{PH} is the photocurrent due to the incident light.

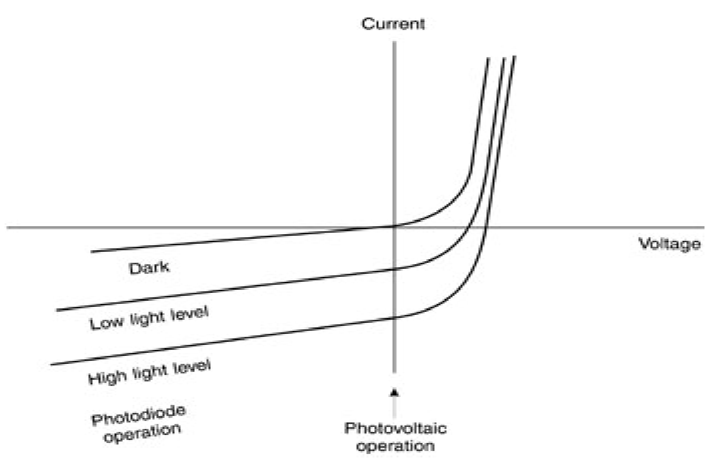

Figure 2: I-V Characteristic of a P-N Juntion biased (photodiode) and unbiased (PV Cell)

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Therefore, a photovoltaic cell is characterized in terms of an open voltage and short circuit current. The maximum power of a panel occurs under short circuit current and open circuit voltage condition. Once a load is attached to the cell, the maximum power is no longer at that bias point and it is the task of a designer to attempt to generate a maximum power condition in order to maximize efficiency. A single photovoltaic cell does not have a significant bias point at maximum power condition. To increase the power cells are combined into modules, and arrays.

Batteries are the storage devices of choice in most applications that use solar energy. However, in some applications one may find that the use of batteries is not the best solution. Capacitors are becoming alternative storage devices, specifically in applications where size and weight are a concern.

Capacitors

A capacitor is a passive element constructed by placing two conductors in parallel separated by an electric insulator (i.e., dielectric). This family of capacitors is classified as electrolytic capacitors. When a potential difference is created between the two plates an electric field is generated and charge accumulates on one of the conductors with an equal charge of opposite polarity on the other conductor. The charge Q is directly proportional to the magnitude of the electric field and the electrical potential difference V is directly proportional to the charge Q. The ratio Q/V is called the capacitance, C, and is given by [3],

$$C = \frac{Q}{V} \tag{2}$$

where, Q and V have units of coulomb (C) and volt (V) respectively, while and C has the units farad (F).

The capacitance is related to the physical structure of a parallel capacitor through the following expression [3]

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} \tag{3}$$

where
A = plate area [m2] = cross section of electric field,
d = distance between plates [m],
ε_0 = permittivity of free space = 8.854 x 10-12 F/m and
ε_r = relative permittivity of the dielectric between the plates [dimensionless].

Capacitors can be combined in series or parallel to achieve a desired operating point. When capacitors are connected in series, the total capacitance is less than any one of the series capacitors' individual capacitances. When capacitors are connected in parallel, the total capacitance is the sum of the individual capacitors' capacitances. By combining capacitors one can achieve a higher current at constant voltage (parallel combination) or a higher voltage at constant current (series combination) [3].

Supercapacitors

Supercapacitors also known as ultra capacitors or electric double layer capacitors (EDLC) are capacitors that have a very high capacitance despite their relatively small size. Unlike the conventional capacitor which stores energy via electrolytic means, this type of capacitor makes use of special electrodes and an electrolyte. There are no chemical reactions taking place like in battery, rather a static charge is generated. Although there are variations on the electrode material, the use of carbon nanopores (50 nm) is the most common. These capacitor structures are made by stacking double layer of highly dense pores separated by of titanium nitride (TiN) (see Figure 3). The ability to stack so many of these pores is what gives rise to the high capacitance [4].

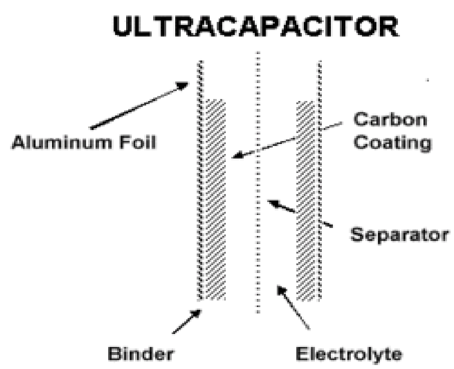


Figure 3: Supercapacitors: Internal Structure

Some advantages with this type of storage devices include long lifecycle, low impedance (fast charging), very efficient and no concerns with overcharging. However, they can only charge to low voltage levels, they discharge relatively fast in a linear behavior, and have low energy density. This technology still is promising for many applications.

Design Description

The design of this robot is based on the IEEE Southeascon hardware requirements for the 2010 competition. The robot was to be powered exclusively by solar energy, there should be no battery of any kind, and the robot had to maneuver on a course for a certain amount of time. Using a clever design of the competition field, the size of the robot was restricted to a maximum height and width in order to conquer a height and width obstacles. The team had two minutes to harvest the energy from high power lights and then 3 minutes to complete a course by traversing through and over certain obstacles such as height and width.

The Robot Design

The first prototypes of the robot were constructed by taking apart other robots, mainly Parallax Boebots, and using their components in lightly constructed frames, but it was concluded early that using servos was not the best way to go. They are slow and consume quite a bit of energy along with the BS2 board used by the Boebot platform. In order to be successful, the design had to primarily meet three basic constraints, structure size, navigation, and power management which are interdependent.

Structure

After several prototypes, it was decided that with the amount of power stored during initial stage, the number of obstacles to conquer should be compromised. The aim was to overcome the width and height obstacles and bypass the ramp obstacle. Even eliminating one obstacle, the design of the body was challenging. The width and height had a great impact on the power, so tradeoffs had to be made. The panels produced more power when closer to the light source, but getting too high compromised the height obstacle. Having a heavy robot consumed power but having it too light compromised traction and thus accuracy in navigation. Another parameter that dictated the shape of the body was the number of panels needed. Ultimately, we went with light wood for the frame and a “butterfly” look when placing the panels as seen in figure 4 (W=8 in., H=16 in. and L=25 in.).

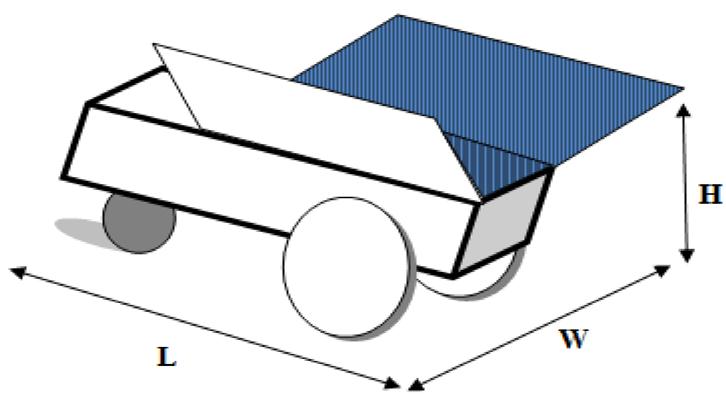


Figure 4: Robot Final Body Structure Diagram

Navigation

In order to maintain the robot on course, some sort of sensors had to be used. Again, dealing with such restricted amount of power there is only so much one can do before the power falls below the minimum required power for motion. Most electronic sensors, such as the ultrasonic and IR sensors, require some self supporting power and normally consume compromising amounts of energy. So, in an attempt to conserve energy, mechanical sensors were implemented. There were whiskers like extensions from the frame with mechanical switches at the end. In later stages of the design IR sensors were implemented in both sides and front of the design. However, most of the navigation was accomplished through code controlled subroutines.

The robot is controlled by the Pololu Orangutan LV-168 Microcontroller depicted in Figure 5(a). It is a full-featured controller for low-voltage robots that can be powered with two or three 1.2-1.5 V batteries while maintaining 5 V operations for its Atmel mega168 AVR microcontroller and sensors. It is mounted on a small (2.15" x 1.9") module and includes two bidirectional motor ports each capable of providing 2 A (continuous).

The design made use of Micro Metal Gear Motors with a 150:1 ratio, Figure 5(b). These are very low power motors and can deliver a very high torque while maintaining a high speed. They have a long (0.365" or 9.27 mm), D-shaped metal output shaft, and the brass faceplate has two mounting holes threaded for M1.6 screws (1.6 mm diameter, 0.35 mm thread pitch).

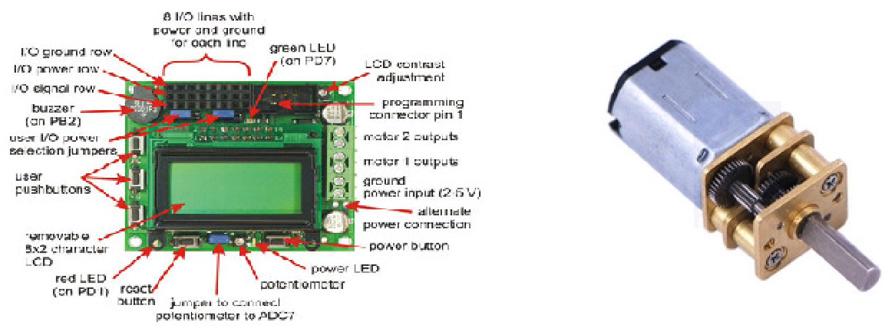


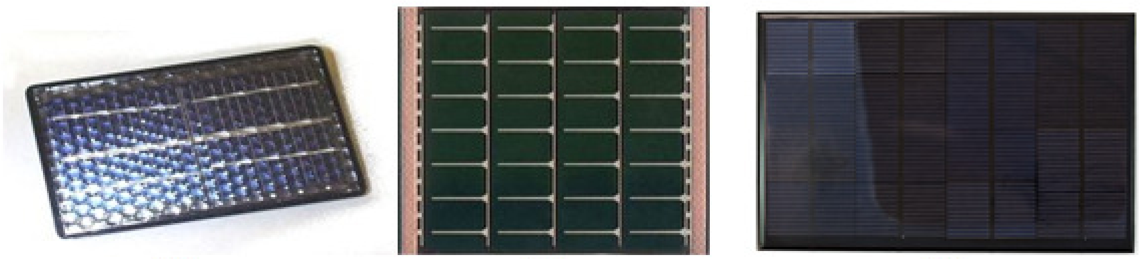
Figure 5: (a) Orangutan LV-168 Microcontroller, (b) Micro Metal Gear Motors

Power Management

The core of this design was the power management. Many factors determined the type of power scheme used. The solar panels had to be efficient and yet affordable, the capacitors had to be configured in a certain way for maximum performance, and circuitry had to be introduced to manage or regulate the power.

Solar Panels

Different types of panels were considered for the design. The first panel investigated was the rigid encapsulated solar panel rated at 0.9V 400mA shown in Figure 6(a). It measures 2.5" X 3.75" X .25" and can be connected in series and parallel using small screws mounted on the embedded frame. Although the current was not bad, this panel had two problems, low voltage and small surface area which called for more combinations. The second type of solar cell used was thin-film modules. The one used were 4.8V 100mA Flexible Solar Panel MPT4.8-150 shown in Figure 6(b). Again, the power was not sufficient and the panels were cumbersome to connect due to a copper strip provided for the connections.



(a) (b) (c)

Figure 6: Solar Panels: (a) Rigid, (b) Flexible Thin-film and (c) High Quality-High Output

Finally, by a series of experiments involving height, capacitor combination, and initial charge condition, we opted to a more rigid and larger panel which would sustain the entire run shown in Figure 6(c). The cell is a high quality solar cell custom made for SparkFun Electronics, a site usually used by hobbyists. It is rated for 8V open voltage and 650mA short circuit but has reached 9.55V open voltage and 850mA short circuit. The high output power was what the design needed but some compromises had to be made such as the ones evident on topology. Termination is a 5.5mm x 2.1mm barrel plug, center positive on a 2m cable. It is a monocrystalline high efficiency cell with a clear epoxy coating with hard-board backing.

The Capacitor Bank and Circuitry

One of the requirements for this project was that there should be no On/Off switch. As a result, the microcontroller was altered to bypass the start push button. This caused a problem because there is a point during charging where the microcontroller wakes up and starts pulling high current from the capacitor bank, which in turns, slows charging and the robot cannot move. There is an initial potential barrier to overcome at start up and to overcome this point more charging capacity is needed. At the same time, the initial charging time must be minimized to increase run time. The solution was to add two additional panels to the original two panel configuration, all connected in parallel. This increased the charging capability of the system.

In order to get a speedy charge initially and still have enough power to run the field several capacitor configurations were tested and one proved more efficient. The capacitors used are 10Farad supercapacitors. Their small internal resistor allows for a fast charging time. Combining them in hybrid format (series and parallel) increased the charging time and slowed down discharging phase (when robot is active). Using Multisim 11.0 and Ultiboard 11.0, software packages from National Instrument, the circuit is simulated and laid out for in-house fabrication. Figure 7 shows the circuit diagram obtained from Multisim 11.0. As can be seen from the circuit diagram, there are two series banks. Bank1 is formed by C_1 in series with C_2 in parallel with C_3 in series with C_4. Bank2 is formed by C_5 in series with C_6 in parallel with C_7 in series with C_8. The final bank is bank1 in series with bank2.

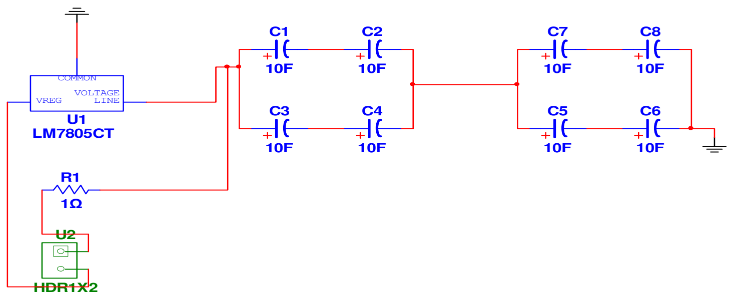
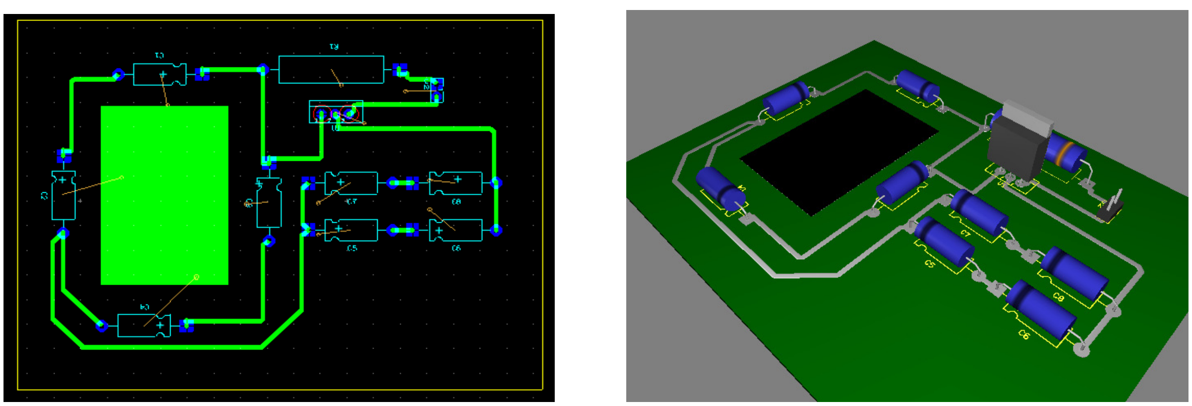


Figure 7: Multisim 11.0 Circuit Diagram

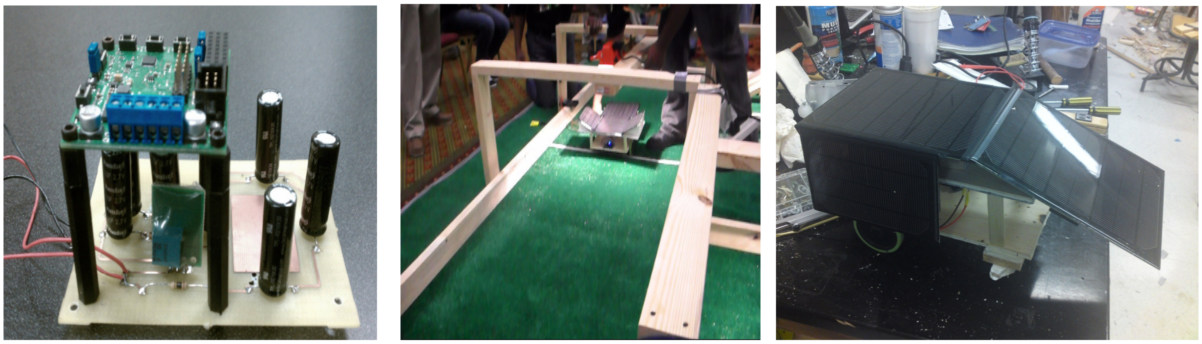


(a) (b)

Figure 8: Ultiboard Circuit Schematic with Capacitor Combinations
(a) 2-D view and (b) 3-D view

The circuit contains an additional voltage regulator and charging resistor. The regulator has an adjustable output and can regulate from 3.0 V to an output between 5V and 12 V DC. This regulator ensures that the microcontroller input voltage is maintained at the required 5 volts. A very low resistor is used for charging time minimizations. Figure 8 shows the 2-D and 3-D circuit layout diagrams used in printed circuit board (PCB) fabrication.

The final circuit and robot after fabrication of the PCB circuit are shown in Figure 9 (a-c).The circuitry is house under the panels.



(a) (b) (c)

Figure 9: Final Design: (a) Circuit after Fabrication, (b) Robot Charging Under a High Power Light Source, and (c) Robot on a Lab Bench

Results

The final robot was able to charge up to 8.5 volts under the light source in about 1 minute. The charge stored in the capacitor bank was sufficient for the robot to reach the mid-field point of a predesigned indoor field, where another light source was available for recharging. Navigation however, proved to be a challenge once the design was moved from field to field. The dependency on code routines to navigate the robot through the field proved to be an issue. As the field texture changes, the robot deviated from course because it required more power to due to higher surface friction. The solution to this problem was the implementation of additional sensors to aid in navigation.

Tests were also conducted using natural sun as the source of energy by placing the robot outdoors. Under the sunlight the panels produced a large amount of energy and the addition of sensors became no longer an issue. The robot could run continuously as long as there is some sun light available.

Conclusion

This capstone project made use of an unconventional method of energy storage that can be utilized in small light weight applications such as for robotics design applications. It shows that by combining supercapacitors in hybrid formation and using additional circuitry it is possible to manage the solar energy stored in capacitors. The stiff constraints imposed by the design requirement used in this project, clearly demonstrates that the use of solar panels-supercapacitors combination can be used to power small scale electronics both indoors and outdoors. The configuration described here can supply small scale devices that fall within the

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power rate specified. However, for devices such as laptops, analysis shows that additional changes to the capacitor bank and circuitry are necessary. With new progresses in the photovoltaic industry, it is a matter of time until laptops are self charging by placing solar cells on the casing and using the same design approach discussed in this work.

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Biography

ANTONIO SOARES is currently an assistant professor of Electronic Engineering Technology at Florida A&M University in Tallahassee, Florida. Dr. Soares obtained his BSEE degree on December 1998 from Florida A&M University, his MSEE degree on December of 2000 from Florida A&M University and his PHD in EE from Florida A&M University on August 2008. His research topics include semiconductor devices and physics, optoelectronics, integrated Circuit design, robotics, nanotechnology, and education. Dr. Soares is current member of IEEE, ASEE, and SHPE.

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