SunaPlayer: High-Accuracy Emulation of Solar cells

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ABSTRACT

Evaluating and debugging solar panel-driven systems is a cumbersome process. The system must be deployed in the wild, software and hardware bugs identified remotely, and the development cycle must be repeated to build a robust system. Emulation platforms for solar panels offer a plausible remedy, however, existing systems have narrow operating range and are not portable. To address these shortcomings, we design, implement, and evaluate the SunaPlayer, a solar panel emulation platform that supports a wide operating current range (430 micro-amps to 1.89 amps) and voltage range (0.02 V to 9.8 V), and can be powered using batteries. SunaPlayer uses a high gain analog device, a PNP darlington transistor, a multi-scale driving and measurement circuit, and a novel state machine based proportional-integral-differential controller to build an accurate non-linear model of the solar panel. We have implemented a fully functional SunaPlayer prototype, and demonstrate that it can emulate a wide range of solar panels with high accuracy, low latency, high sensitivity, and low power consumption. The design methodology for the SunaPlayer can be used to build systems that model hard to emulate non-linear devices.

Categories and Subject Descriptors

B.m [**Hardware**]: Miscellaneous

General Terms

Hardware Implementation

Keywords

Solar panel, Emulation, PNP darlington

1. INTRODUCTION

Renewable energy-driven systems are key to a self-sustainable society. The increase in the number of renewable energy-driven homes, sensors, and compute systems bear ample testimony to the growing popularity of such self-sustainable systems. Solar panels are the most popular renewable energy harvester. Solar or Photovoltaic (PV) panels are a non-linear device that harvest energy from incident light such as natural sunlight or light from artificial sources like incandescent and fluorescent lamps. PV panels scale from small panels used for micro-harvesting indoor light, medium sized panels that power sensing and environmental monitoring systems, to large PV arrays that power buildings. Irrespective of their size and the type of systems they power, evaluating and debugging solar panel-driven systems is a tedious and cumbersome process. Debugging such systems involve deploying them under realistic conditions, performing remote diagnostics, evaluating software and hardware bugs, and then repeating the development lifecycle. Rapid prototyping, hence, is difficult, if not infeasible for such systems. Therefore, in lieu of time and resources, most of the evaluation for PV panel driven systems is performed in a *single* setting. Such an evaluation lacks external validity and it is often unclear how performance would be affected when the environmental conditions change.

Solar panel emulation is a plausible solution to streamlining the process of evaluating solar panel driven systems. The goal of the emulation is to perform evaluations of solar-

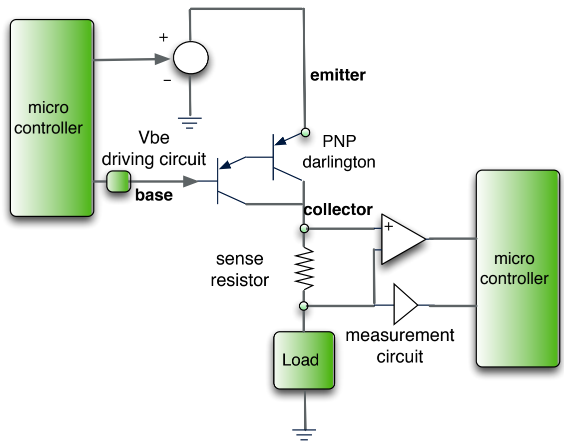

Figure 1: SunaPlayer uses a non-linear analog device, a PNP darlington transistor, a multi-scale driving circuit, and a high resolution measurement circuit, to emulate the non-linear characteristics of a solar cell. The driving circuit is controlled by a state-machine based PID controller running at a micro-controller.

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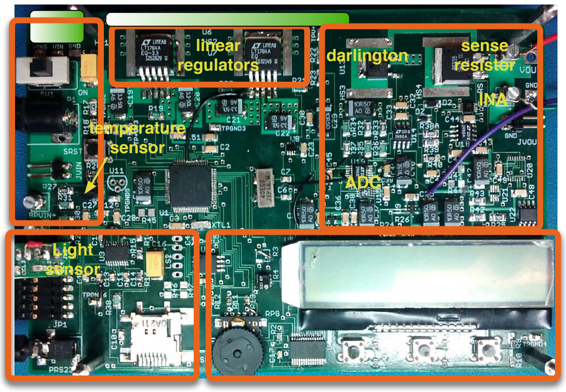


Figure 2: The SunaPlayer prototype.

panel driven systems in the laboratory. The emulation is not intended to replace the use of solar cells in the deployed systems. The emulation can help determine (a) which solar cells to use and (b) address bugs in the system quickly by rapid prototyping and evaluation in the lab. While there are systems (high-end power supplies for instance) available in the market that can perform solar panel emulation, they are expensive and not portable.

A solar cell emulation platform emulates the current and voltage characteristics of a solar cell, modeled by its IV curve. The goal of the emulator is to power a *load* as if it were powered by an actual solar cell. Hence, a wide range of IV traces collected from a variety of solar cells under different lighting and temperature conditions can be *replayed* in a laboratory setting to power and test the system being evaluated. Such a device can radically ease the development lifecycle of solar panel powered devices. The existing solar emulation platforms, however, are limited in several ways. For example, most emulators use linear *digital* solutions and have limited output current range [1]. The key challenge to emulating solar cells across a wide operating current/voltage ranges is to build accurate non-linear models for solar cells of different sizes, and under different lighting and temperature conditions. Since existing system use linear devices to emulate a solar cell (a non-linear device), the emulators are fine tuned and sensitive only in a narrow operating range of output voltages and currents [1]. Secondly, most emulators rely on high performance personal computers to compute the operating current and voltage values on an IV trace of a solar cell for a given load. Therefore, the system is powered using wall sockets and is not portable. For several applications, however, portability is paramount. For instance, consider a solar panel driven mesh network where the system designer wants to determine the type and size of the solar panel he should use. For such an application, the emulator can be programmed with a set of solar panel IV traces and deployed with the mesh nodes. The emulator can then in-vitro sense the ambient light intensity and temperature and select the appropriate solar panel IV curve to emulate. For such an emulator to be practically useful, it should consume minimal power, and should be portable.

[1]Commercial power supplies that can be used as solar cell emulators are very expensive and are not portable [2].

To address the above limitations, we present the design, implementation, and evaluation of the SunaPlayer, an emulation platform for solar panels spanning micro solar cells to large sized solar panels. The overall circuit design and the prototype SunaPlayer is illustrated in Figures 1 and 2. SunaPlayer uses a versatile non-linear *analog* device, a PNP darlington transistor as the current source with a diode for emulating a solar cell. The PNP darlington transistor has an IV characteristic similar to a solar cell. The SunaPlayer uses a multi-scale driving and measurement circuit, and a novel proportional-integral-differential controller to in-vitro build an accurate non-linear model of the solar cell for a given lighting condition. The emulator takes IV curves as input and emulates the solar cell for a given load. Generating IV curves for solar cells is out of scope of the SunaPlayer. However, there are systems that can profile solar cells accurately (e.g. Ekho system [3]). The SunaPlayer supports a wide operating range, spanning output currents from 430 μA to 1.89 A (at low voltages; four orders of magnitude) and output voltages from 0.02 V to 9.8 V (three orders of magnitude), and can emulate solar cells with an accuracy of close to 99%. The SunaPlayer does not make any assumptions on the type of load being powered by the harvester. It can power linear and non-linear loads, combination of storage devices like capacitors and batteries, or devices that are directly powered by the harvester without a storage element.

Research contributions: The design, implementation, and evaluation of the SunaPlayer presents the following novel research contributions. (1) **Novel hardware design:** Unlike previous work that use linear devices to emulate solar cells, the SunaPlayer emulates the solar cell using a high gain non-linear *analog* device, a PNP darlington transistor, whose IV characteristics are similar to a solar cell. The PNP darlington is controlled using a multi-scale driving circuit that allows the SunaPlayer to be sensitive across a wide range of output currents and voltages, and across a wide range of lighting and temperature conditions. (2) **Novel software controller:** SunaPlayer uses a novel state machine based software controller that uses PID logic, caching, and device-specific optimizations to accurately control the PNP darlington. The iterative controller helps the SunaPlayer to build an accurate model for the solar cell without a priori information on the load characteristics. (3) **Functional prototype:** We have prototyped a fully functional SunaPlayer device, and evaluate it in the context of two applications: emulating small, medium, and large sized solar panels, and in-vitro determination of the appropriate solar cell for a given system. We show that the SunaPlayer can emulate solar panels with IV characteristics ranging from 430 μA – 1.89 A (4 orders of magnitude) and 0.02 V — 9.8 V (3 orders of magnitude) with an accuracy of more than 99%.

2. BACKGROUND AND CHALLENGES

Before describing the SunaPlayer design, we provide an overview of PV cell operation. Photovoltaic (PV) panels are made of PV modules, that convert incident light energy into electric charge. A PV cell is modeled by a current-voltage or IV trace (Figure 3) , that is characterized by an open circuit voltage (OCV) (the voltage drop across the panel leads when there is no load, i.e., voltage limit), a short circuit current (SCC) (the current draw when the leads are connected using a shunt, i.e., current limit), and the maximum power point (MPP) (the maximum power harvested by the solar

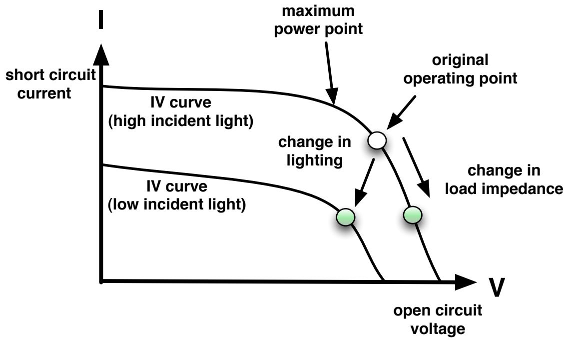


Figure 3: The figure shows two IV curves for a solar cell. The IV curve is characterized by the short circuit current, open circuit voltage, and the maximum power point. Each point on the IV curve corresponds to a load impedance. Each IV curve is a function of the ambient light intensity and temperature. The IV characteristics are highly non-linear.

cell ($I \cdot V$), i.e., power limit). The IV characteristics of the panel between SCC and OCV is highly non-linear [4], and each point on the curve corresponds to a load impedance. The PV cell acts as a current source, and if the load current increases, the voltage across the load drops. The IV curve of a solar panel, and thus the operating point of the panel, also changes with ambient temperature and incident light intensity. The goal of a solar emulation platform is, therefore, to assure that the voltage and current supplied to an attached load is on the appropriate IV curve, for a wide range of solar cells. We next describe the SunaPlayer's hardware and software architecture.

3. HARDWARE ARCHITECTURE

The SunaPlayer employs a hardware architecture that supports solar panel emulation for a wide range of open circuit voltages and short circuit currents. The overall SunaPlayer hardware circuit is illustrated in Figure 1. The primary emulation device is a PNP darlington transistor. Using a darlington for emulating solar cells is a novel approach. This non-linear analog device has a large operating range, is power efficient, and has an IV response close to that of solar cells. The device is controlled by a driving circuit. The output load voltage and current is measured using a multi-scale measurement circuit. A low power 16MHz PIC micro-controller senses the output current and output voltage, and iteratively controls the driving circuit to output the appropriate voltage and current.

The SunaPlayer can operate in two modes: (1) offline mode; and (2) online mode. In the offline mode, the system is programmed with a set of solar panel IV traces. The SunaPlayer chooses an IV trace to emulate and automatically finds the correct operating voltage and current on the IV trace for a given load. The IV traces could correspond to solar panel profiles for different lighting and temperature conditions. They could also correspond to IV curves for solar panels of different sizes and compositions. If the solar panel traces are not collected experimentally, the system can also use IV traces from datasheets. In the online mode, the SunaPlayer senses the ambient light intensity and selects the appropriate IV curve to emulate. The online mode

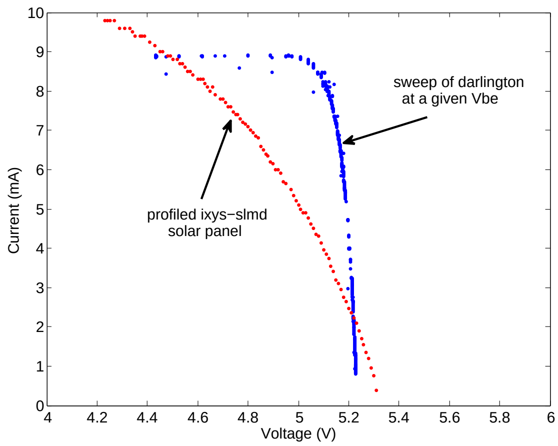


Figure 4: The figure shows a part of the IV curve of a profiled solar panel at 7500 lux. The solar panel has an open circuit voltage of 5.5V and a short circuit current of 10 mA. The IV trace is generated by varying the output load powered by the solar panel under an incandescent lamp. The blue line is the IV sweep for the PNP darlington and is generated using a set of load impedances. The figure shows that the darlington and the solar cell have similar IV characteristics, and they behave as a current source with a diode.

is useful for testing a system on a set of solar panel traces in an actual deployment. It is possible to add a third mode of operation in which the emulator uses an analytical model of the IV curve. This would require a preprocessing step that approximates a complex analytical model (one that possibly requires logarithmic and exponential function evaluations) as a set of piece wise linear functions. This mode will be implemented in the future.

The SunaPlayer can power a wide range of loads or charge a wide range of storage devices. For example, the emulator can charge a battery, a super-capacitor, or a combination of storage devices and charge controllers. The emulator can directly power a sensing or embedded system without a storage device. We next describe the hardware components of the SunaPlayer.

PNP darlington device: Existing devices for emulating solar panels assume a constant voltage source like a capacitor powering the load [1], or use linear digital solutions like programmable voltage regulators [5] to emulate a solar cell. Ekho [1], for instance, assumes a voltage source such as a capacitor charging the load. A storage device like a capacitor provides a deterministic output voltage across the load, and the emulator can measure this voltage to determine the output current on the solar cell's IV curve. Unfortunately, such a system cannot be used in configurations where the load is directly powered by the solar panel without a storage device or if the system uses a combination of a charge controller circuit and two or more storage devices like capacitors and batteries. The other solution is to use a linear regulator to generate the load voltage and current. The output of the linear regulator is divided using a resistor divider, and appropriate output voltages are produced using a digital potentiometer. However, such a solution suffers from several drawbacks. First, the sensitivity of a linear device is limited for a wide range of current and voltage outputs. The digital potentiometer used to generate the output voltage usually has 1024 intervals, which provides the same resolution when emulating very small current and voltage outputs and large current and voltage outputs. Hence, the device is not sensitive to small changes in load currents and voltages or small changes in light intensity. It might be possible to get a wider operating range using multiple linear regulators. However, the power consumption, given the efficiency of most linear regulators, would be high. Moreover, with multiple PNP darlingtons the SunaPlayer can have an even wider operating range. Second, and more importantly, a linear regulator is a voltage source and may not be appropriate for emulating a current source like a solar panel. To understand why, consider the following property of a linear regulator. If the load current increases, the regulator will supply the current without any drop in the voltage. Hence, the system will have transients that do not mimic a PV cell.

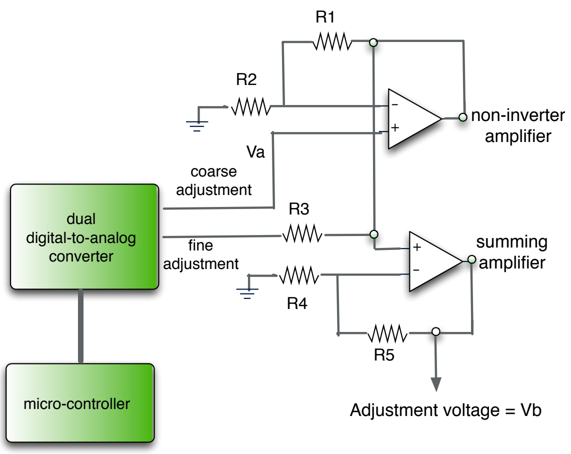


Figure 5: The multi-scale circuit to drive the base voltage of the PNP darlington. The circuit uses a combination of a fine adjustment that provides the SunaPlayer with the ability to fine-grain control the changes in V_{be} and a coarse adjustment that helps generate base voltages close to $V_E(V_+)$ for small output currents.

SunaPlayer uses an analog non-linear device, a PNP darlington transistor to emulate solar panels. A PNP darlington is a high gain non-linear device that acts as a current source (a corresponding NPN darlington transistor can also be used as a current sink). It is a pair of bipolar junction transistors (BJT) connected in a common collector configuration. This configuration creates a device with a higher current gain compared to a single BJT. The gain of the darlington can be approximated as $\beta_1 \cdot \beta_2$, where β_1 and β_2 are the individual transistor gains. The load is attached to the collector, while the load current and load voltage can be controlled using the bias voltage V_{be}—the voltage drop across the base and the emitter. The darlington overcomes the drawbacks of a linear digital device (voltage regulator) and a single BJT. First, the darlington can source a wide range of currents and voltages. By adaptive fine-grained control of the base-emitter voltage drop, the output current and the output voltage can be controlled with a fine resolution across a wide range of output current and voltage. Moreover, the BJTs allow a non-linear rescaling of the quantization error over a long range. In particular it allows better proportional error at lower currents and voltages while supporting a wide operating range. Second, since the current gain of the device is high (unlike a single BJT), the input base current required to generate a high output current is low. Hence, the system can be controlled using low power micro-controllers. Third, for a fixed value of V_{be}, the output characteristics of a darlington is close to the output characteristics of a photocell. As illustrated in Figure 4, if the load current increases, the voltage will drop as it does with a photocell. Hence, the system responds more accurately to rapid load perturbations. Finally, the darlington is also an efficient non-linear analog device that can be current limited and voltage limited by appropriately setting V_E, the emitter voltage.

The darlington transistor has advantages over a linear regulator when emulating solar cells; however, accurate and fine-grained control of the device presents several technical challenges. The darlington is a non-linear device and the output characteristics of the device are difficult to model. Moreover, our system does not make any assumptions on the load characteristics; hence, in the absence of any analytical models that characterize the collector current and voltage as a function of the bias voltage (V_{be}), it is challenging to design a low latency controller that finds the operating point on a solar cell's IV curve accurately. Additionally, like any transistor, the darlington chain operates in three modes—cutoff, saturation, and active modes. Unfortunately, if the darlington is in saturation mode, it takes a long time to switch from saturation to active state, and a high saturation voltage can lead to high power dissipation when large output currents are required. Therefore, it is important to assure that the darlington does not transition to saturation mode. We address these challenges in our design of the driving and measurement circuit and the novel state machine based controller described in §4.

Multi-scale driving and measurement circuit: The driving circuit accurately sets V_b (base voltage) that determines V_{be} (base-emitter drop), the bias voltage that controls the collector (load) current and voltage. Given the non-linear characteristics of the darlington, for high sensitivity at low and high current ranges, the driving circuit for the darlington must provide variable scale control for different output ranges. Moreover, the darlington is a high gain non-linear device, and hence, for high sensitivity, the driving circuit that sets V_b must provide very fine-grained changes in V_b. This will allow the SunaPlayer to respond to small changes in load impedance and light intensity. But at the same time, it must be possible to set V_b close to $V_e(V_+)$, when very small output currents and voltages are desired. We solve the problem using a multi-scale driving circuit, illustrated in Figure 5.

The darlington's base voltage is controlled by dual 16-bit DACs with an SPI interface to the micro-controller. The DACs output a fine adjustment voltage and a coarse adjustment voltage, as illustrated in Figure 5. To provide coarse scale adjustments, V_a (in the figure) is fed to a non-inverting opamp stage with a gain of $(1 + R_1/R_2)$, effectively 5 for our circuit. The fine-grained control line is combined with the coarse grained adjustment using an amplifier and a set of resistors that create a summing amplifier. Effectively, it provides a V_{adj} that is equal to $x \cdot V_f + y \cdot V_c$ where V_f is the fine grained voltage and V_c is the coarse grained line. x is small, 0.5 in our case, and y is close to 7.5. The fine

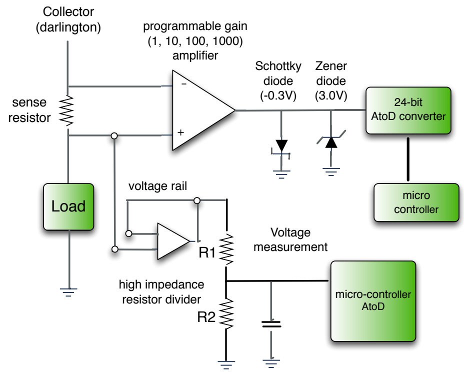


Figure 6: The multi-scale circuit for measuring the output voltage and the output current. The instrumentation amplifier with gains of 1, 10, 100, and 1000 allows measuring low and high currents accurately, and provides multiple resolutions of output measurements. The diodes clamp the output voltage and allows accurate measurements using the ADC. The voltage is measured using a high impedance rail that minimally effects the load currents.

adjustment voltage has a resolution of 22.9μV and a range of 0 to 1.5V. The coarse adjustment voltage has a resolution of 858μV with a range of 0 to V_+. The fine adjustment range of 1.5V allows the darlington to be biased from cutoff to high current levels by only varying the fine adjustment voltage. The coarse adjustment, on the other hand, allows the darlington base voltage to be set close to V_+, generating a small bias, and small output voltages and currents. This multi-resolution circuit allows both fine grained and coarse grained adjustment of V_b, and provides the SunaPlayer the flexibility to produce very low output currents and high output currents, and at the same time be highly sensitive to small changes in the load impedance.

In the SunaPlayer design, the darlington's emitter voltage, V_e, is controlled by a V_+ programmable power supply ($V_e = V_+$). The value of V_+ is varied by changing the value of a digital potentiometer, programmable from the micro-controller using a SPI interface. The voltage, V_e, can be varied from 5V to 10V. The digital potentiometer has 256 steps and the change in V_+ from a single LSB step is a function of the voltage range. For example, if $V_+ = 5$V, a least significant bit (LSB) provides a change in V_+ of 9.7mV while for a $V_+ = 10$V a LSB provides a change of 114mV. This fine resolution allows for accurately setting V_e on the darlington. The value of V_+ depends on the solar cell being emulated. V_+ helps limit the output voltage of the emulator, similar to the voltage limiting characteristic of a solar cell. However, to avoid the darlington from transitioning from active to saturation mode, V_+ must be higher than the open-circuit voltage of the solar cell.

The load current is measured by the voltage induced across a low tolerance 1 Ω sense resistor, attached to the collector (Figure 6). An instrumentation amplifier, with programmable gains of 1, 10, 100, and 1000, amplifies the voltage across the sense resistor. The use of multiple gain levels allow very accurate current measurements for very low and high currents. Theoretically, the measurement circuit can measure few nanoamps of current accurately. For highly accurate measurements, the voltage output from the amplifier is clamped using diodes, so that the output voltages do not fall below -0.3V or is above 3.0V. The first diode is a Schottky diode that prevents the voltage from dropping below -0.3V , preventing negative voltage drops. The second diode is a Zener diode that prevents the voltage from rising above 3.0V. Another important consideration for our measurement circuit design is the thermal properties of the sense resistor. Under high output load currents significant power may be dissipated. A one ohm resistor with a 2A output current dissipates 2W, and even with a heat sink the temperature of the resistor may rise. The temperature coefficient of resistance, therefore, is taken into account in the current calculations. To measure the load voltage, a high input impedance voltage follower amplifier is used (illustrated in Figure 6). This allows accurate voltage measurements with very minimal loading due to the measurement circuitry. The load current sensing circuits may be calibrated using two current sources (100 mA and 200 μA) that are optionally connected to the load using a solid state switch. The primary processing unit of the SunaPlayer is a 16 MHz PIC18F87K22 micro-controller with an additional 16 MBit flash, serial I/O, and a microSD card reader slot to store IV traces. We have designed, implemented, and assembled a fully functional prototype of the SunaPlayer, illustrated in Figure 2. The boxes illustrate the different components of the 4-layer printed circuit board.

4. SOFTWARE ARCHITECTURE

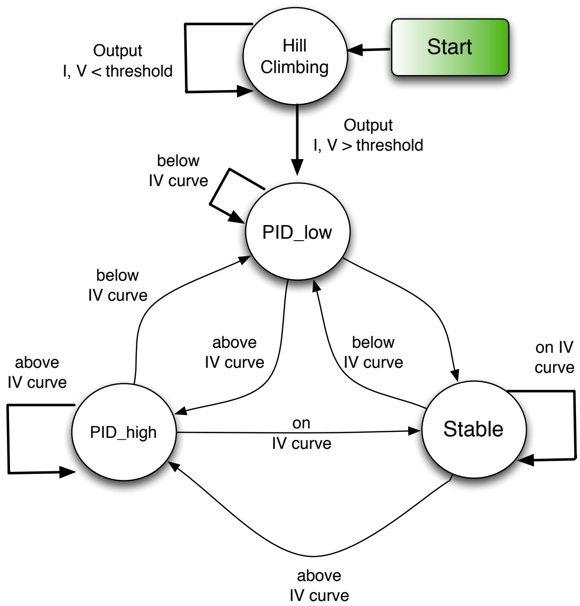


Figure 7: The state machine for our software controller. The controller determines the base voltage V_b that must be applied to generate a bias voltage V_{be}. The state machine starts in a `hill climbing` state that transitions the darlington from cutoff to active mode and stabilizes the output voltage. The `PID_low` and `PID_high` states use PID controllers when the output voltage and output current values are below and above the IV curve respectively. The SunaPlayer is in a stable state when the output voltage and current is on the IV curve.

The SunaPlayer does not make any assumptions about the characteristics of the load attached to the harvester. To power any arbitrary load, the software controller that sets the base voltage must address two key research challenges. First, the load impedance is unknown, hence it is impossible to a priori determine the operating point on the IV curve of the solar panel. Secondly, while the characteristics of a PNP darlington is close to a PV cell, like a PV cell, accurately modeling the non-linear relationship between the inputs (bias voltage V_{be} and light intensity) and the output current and output voltage is difficult. To address the two challenges, the SunaPlayer leverages a novel controller for the base voltage that uses a finite state machine and a proportional-integral-derivative (PID) logic that quickly converges to an operating point on the solar panel IV curve without apriori knowledge of the load impedance and the relationship between the input and output variables of the darlington.

State machine-based controller: The idea underlying the software controller is simple. The micro-controller applies a bias voltage (V_{be}) by changing the voltage on the base of the darlington. This produces an output voltage and output current at the collector (load). The output voltage and the output current is sensed using our multi-scale measurement circuit and read by the micro-controller. The micro-controller then determines the change in V_{be} (ΔV_{be}) that must be applied to the darlington base to reduce the *error* between the operating point on the solar cell IV curve and the present output current and voltage. Since the actual operating point on the IV curve is unknown, we use a heuristic to determine the error. The solar panel IV traces are offline modeled as a set of polylines. We apply the k-means algorithm [6] on the IV trace and then use linear regression on the clustered points to determine the polylines. An example set of polylines for a solar panel IV trace is illustrated in Figure 8. The SunaPlayer stores the last four output voltage and current values generated by the darlington by varying V_{be}, performs a linear regression on these stored points to generate a line. The controller then finds the intersection of the modeled line and the polylines generated from the panel's IV trace. The intersection point is the *predicted* operating point for the given load. The error is calculated as the Manhattan [7] distance between the predicted operating point and the point corresponding to the present output voltage and current. Note that the load might be non-linear and our algorithm approximates the load's IV characteristics using a set of piecewise linear functions. The approximation of the IV trace of the solar cell as polylines and the load characteristics as a set of linear functions reduces the computational complexity of finding the *predicted error*, and can be efficiently implemented on a micro-controller platform.

For every V_{be}, an error is calculated, and the system uses a proportional-integral-differential (PID) controller to iteratively reduce the error. A PID controller is a generic feedback-based controller that is used for industrial applications. If there is no apriori knowledge of the underlying process, the PID controller is considered the best performing controller [8]. The PID controller, in our application, determines ΔV_{be}, the change in V_{be} in the next iteration. ΔV_{be} is a function (summation) of three entities. (1) proportional error ($K_1 e$), where e is the error described above. (2) integral error ($I \int e_t dt$), which is a summation of the errors in the previous iterations of the algorithm, and the (3) differential

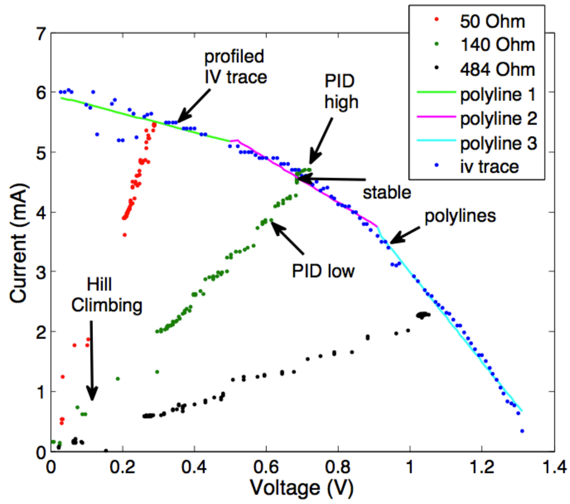


Figure 8: The figure shows an example run of the state machine based controller for three load impedances of 50, 140, and 484 Ωs. The figure shows that the output current values in the `hill climbing` state is randomly spread, but it stabilizes and shows a linear trend in the `PID_low` state since the load is a linear device. The figure also shows the `PID_high` and `Stable` states.

error ($D \cdot de/dt$) is the slope of the error over time. K, I, and D are constants for the proportional, integral, and differential errors. The three types of errors help faster and more accurate convergence in our application over using a purely proportional controller. The differential error, for instance, can help determine when the system is close to the actual point of operation while the integral factor helps smoothen errors caused by darlington transients. Note that the error e, described above accounts for hardware error induced due to the measurement circuit, leakage currents of the darlington, and circuit noise.

While applying the PID approach, we ran into several practical challenges due to the non-linear characteristics of the darlington. For instance, when the output voltage and current is zero, the darlington is in cutoff mode. On increasing V_{be}, the darlington switches from cutoff to active mode, but it takes a finite amount of time before the output of the darlington stabilizes. Hence, calculating the error using the extrapolation method described above can be erroneous during this stage. Additionally, given the non-linear characteristics of the darlington, we have found that the optimal PID constants that converge to the operating point when the output voltage and current values are below the IV curve are different from the PID constants when the output voltage and current values are above the curve. This is because the increase in V_{be} required to switch the transistor on is different from the decrease in V_{be} required to proportionally switch it off.

Our controller, therefore, is a state machine that operates in four states (illustrated in Figure 7), depending on which region of the IV space the output current and output voltage lies. The first state is a `hill climbing` stage where the darlington switches from cutoff to active mode and its output stabilizes. For our application, we determined experimentally that the controller should transition from the

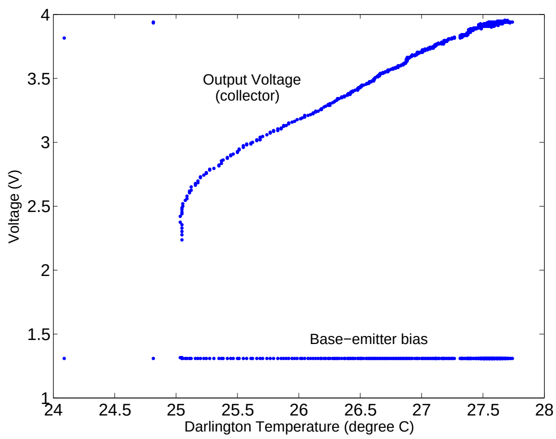


Figure 9: The figure shows that the output voltage of the darlington changes by 1.5V when its temperature varies by 2.5°C. The bias voltage (V_{be}) is kept constant. The temperature change occurs because a large 400 mA current is sourced by the darlington, causing high heat dissipation. This artifact occurs because the output gain of the darlington changes logarithmically with temperature.

`hill climbing` state to the `PID_low` state when the output voltage and output current is more than 25% of the maximum voltage and current in the IV trace. The system stays in the first PID state, `PID_low` till the output voltage and output currents lie below the IV curve. As soon as the system reaches the IV curve, it transitions to the `Stable` state and the controller stops changing V_{be} as the operating point has been reached. If the system overshoots the IV curve, it transitions to the `PID_high` state where a different set of PID constants are used. Finally, the system can move out of the stable state if the load impedance changes or a different IV curve is emulated. The load impedance can change if subsystems like the radio module is switched on or off and a new IV curve is emulated if the ambient light intensity changes. Figure 8 shows an example run of the state machine controller as it transitions through the states. The load is a resistor, a linear device. As shown in the figure, in the `hill climbing` state the output voltages and currents are not stable and do not show the linear trend that is characteristic of a resistor. However, in the `PID_low` state the outputs are stable and show a linear trend and converge to an operating point on the IV curve, modeled by polylines.

Latency optimization: To improve the latency of convergence to an operating point, in the `Stable` state, the SunaPlayer caches V_{be}, the output current, and the output voltage in a lookup table (LUT). The SunaPlayer can then use these cached values to improve the latency of convergence when the desired output voltage and current is close to a cached value. When the SunaPlayer controller determines the predicted operating point on the IV curve, using the extrapolation method described above, it linearly searches the entries in the look up table to find the output voltage and output current that has the shortest Manhattan distance to the predicted value. The system then sets the bias voltage, V_{be} in the LUT entry. Caching operating points reduce the number of iterations required in the PID state to converge.

Brand	Incident Light	OCV	SCC
Cymbet	7500 lux	1.3V	6 mA
Ixys	13000 lux	5.5 V	10 mA
Solamax	13000 lux	2.9V	100 mA

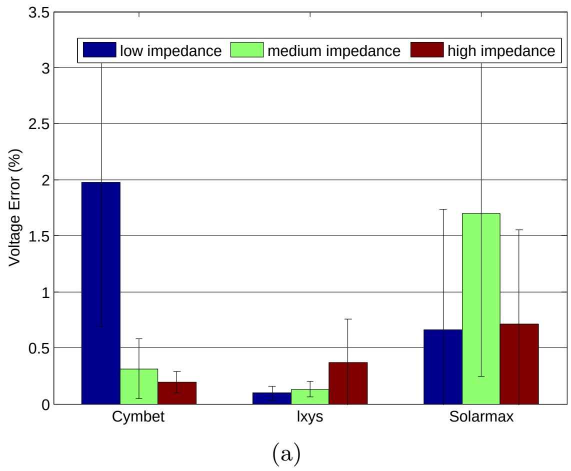
Table 1: The three characteristic solar panels and ambient light intensity used to evaluate the SunaPlayer.

Practical implementation challenges: At high currents and high voltages, the thermal properties of the darlington creates a practical challenge, illustrated in Figure 9. When a current of above 400 mA is sourced by the darlington, the output voltage of the darlington (load voltage) changes from 2.5 to 4 volts, even though the bias voltage V_{be} is kept constant at 1.3 V. A closer look shows that the temperature of the darlington changed from 25 to 28^oC during the course of the experiment. Unfortunately, the gain of the darlington changes with temperature, hence, if its temperature changes, the output current and voltage rises steadily even if the bias is constant. Therefore, for deterministic results, the temperature of the darlington must be kept constant when changing V_{be}. In our prototype, we use a processor fan on top of the darlington to dissipate the generated heat. This helps minimize the temperature fluctuation of the system.

5. EVALUATION

We evaluate the SunaPlayer while focussing on the following questions. **(1)** How accurately does the SunaPlayer emulate solar cells? What is the range of output currents and voltages that the SunaPlayer can support? **(2)** What is the SunaPlayer's latency of convergence to an operating point on the IV curve? How sensitive is the device to changes in load impedance and ambient light intensity? **(3)** What is the energy consumption of different components of the SunaPlayer? While answering these questions, we also present micro-benchmarks on system overhead and cost, and associated accuracy and latency tradeoffs in the system.

Experimental setup: We evaluate the SunaPlayer in the context of two applications. The first application is *offline panel emulation*. For this application, the SunaPlayer replays IV traces from solar cells under low, medium, and bright lighting conditions. For the second application, *solar cell comparison*, the SunaPlayer determines the appropriate solar cell IV curve to emulate based on ambient light intensity when the system is deployed in the wild. For the first application, we generate IV traces for three solar cells under low, medium, and high ambient lighting conditions. To generate IV traces under controlled lighting, we use a programmable incandescent lamp, whose light intensity is controlled by regulating the current draw using a transformer. The incident light intensity is continuously monitored using a light meter. The operating points on the IV trace of the solar cell is generated using a high resolution programmable load. A summary of the incident light (in lux), type of solar cell, the short circuit current, and the open circuit voltage of the solar cell under the given lighting conditions is described in Table 1. In our experiments, we use these three IV traces as they represent three characteristic points in the spectrum of output voltages and currents that the SunaPlayer can support. We use the programmable load and a resistor-capacitor box to emulate loads that the SunaPlayer powers.



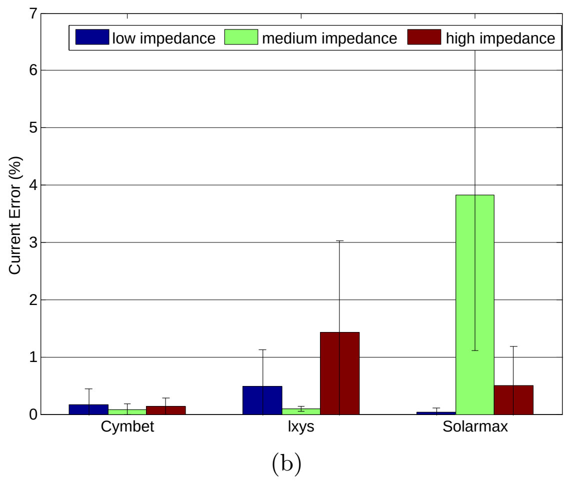


Figure 10: (a) The figure shows the accuracy of converging to an operating voltage on the IV curve. (b) The figure shows the accuracy of converging to an operating current on the IV curve. The impedance values for the load was varied from 45 Ω to 2.1 $K\Omega$s. The low impedance values correspond to the low voltage, high current region of the IV curve, the medium impedance is close to the maximum power point, and high impedance correspond to the high voltage, low current region of the IV trace. The average accuracy is close to 99% for both current and voltage for the wide range of solar panels and impedance values.

We used resistive loads for baseline evaluation of the system. Performing evaluation on CMOS (non-resistive) loads is a task in the future. The challenges that we envision when testing the SunaPlayer on non-resistive loads is detailed in §7. We note that the SunaPlayer can support higher currents and voltages than the Solarmax and Ixys panels in Table 1. However, generating IV traces for very high output currents and voltages require direct sunlight that is impossible to control and regulate. Therefore, we have performed a proof of concept evaluation on synthetic operating points and verified that the SunaPlayer can emulate high output currents and voltages.

Range and accuracy: We first evaluate the output current and voltage range that the SunaPlayer can support. The range is defined as the smallest and largest output current and output voltage that the SunaPlayer can generate with high accuracy. To determine the smallest voltage and smallest current, we set V_+ to the smallest value that our system can support (5V), and then reduce the bias voltage (V_{be}) to as small as possible so that the darlington is in active and not in cutoff mode. This bias voltage switches on the darlington by the smallest possible amount. We then try a set of load impedances and measure the voltage drop across the load and its current draw with a high resolution multimeter and our measurement circuit simultaneously. We determine the error in the measurement, and if the error is below a threshold, we assume that the system can generate the output voltage and current. To measure the largest possible current and voltage, we set V_+ to the maximum value that the SunaPlayer can support (10V). We then increase the bias voltage so that the darlington is in active mode and not in saturation and measure the largest possible output voltage and current. Through this experiment, we found that the SunaPlayer can accurately generate output voltages spanning 0.02 V to 9.8 V (at low currents), and output currents from 430 μA to 1.89 A (at an output voltage of 2.12 V). The analog-to-digital converter induces a noise of +/- 1.5% when measuring low voltages around 0.02 V, and induces an error of 0.03 V when measuring high voltages (9.8V). It also induces a 7% error at ultra-low currents. The error is caused by an offset voltage of the instrumentation amplifier. For the higher current values, the heat dissipated by the darlington is a bottleneck. Even with the processor fan, there is a steep rise in the darlington temperature. We believe that with a passive heat sink, the range can be further improved. In spite of the above, the SunaPlayer can

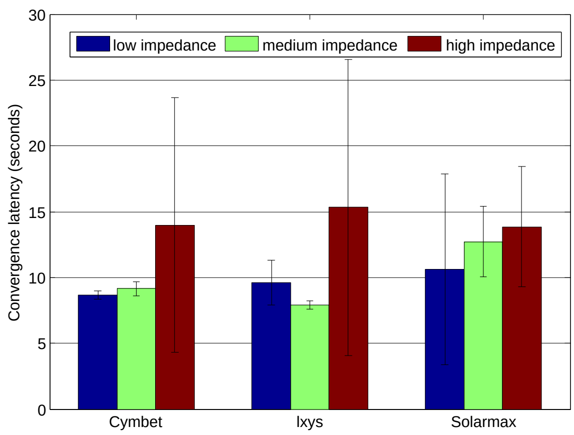


Figure 11: The figure shows the latency of converging to an operating point for the SunaPlayer. The worst case latency is less than 10 seconds. This is absolute worst case latency of convergence when the SunaPlayer starts at a cutoff state. In the common case when the devices transitions from one IV curve to another, the latency is less than 2 seconds.

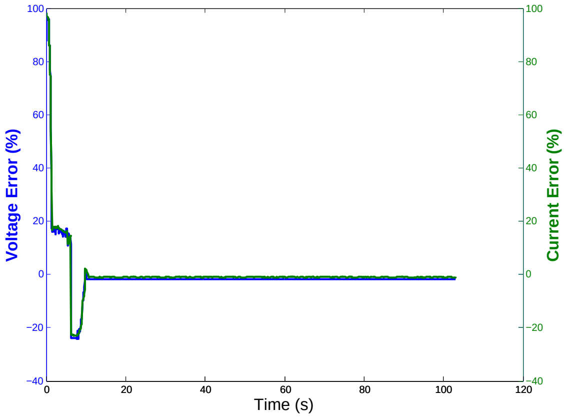


Figure 12: The error in the output voltage and output current as a function of time. The error stabilizes close to 0% at 5 seconds, which is the *worst* case latency of the system. If a lower accuracy is acceptable to the application, the latency can be reduced. For example, at an error of 18%, the latency is less than a second. The negative error corresponds to values of the output voltage and current above the IV curve.

support output voltages that span three orders of magnitude and currents that span four orders of magnitude. The system can, therefore, emulate a wide range of solar cells under a wide range of lighting conditions.

We next evaluate the accuracy of the SunaPlayer. The accuracy of converging to an operating point on the IV curve is calculated as a duple $[(C_I - A_I)/A_I, (C_V - A_V)/A_V]$, where A_V, A_I are the operating voltage and current for the given load and C_V, C_I are the output voltage and current of the SunaPlayer when the system is in the `Stable` state (see Figure 7). To determine the accuracy across a range of solar panels and lighting conditions, we perform our experiments in a laboratory setting using the three IV traces described in Table 1. For each IV trace, the SunaPlayer powers small, medium, and large loads. These loads correspond to the [low voltage, high current], [medium voltage, medium current], and [high voltage, low current] regions of the IV trace and vary from 45 Ω to 2.1 KΩs. We perform five experimental runs for every load and every IV trace, and calculate the average accuracy and the standard deviation. Figure 10 plots the voltage and current convergence errors for the SunaPlayer for the three IV traces. We find that the average accuracy is high–close to 99% for most cases. The overall accuracy of converging to the correct current value is higher than the voltage values. This is because the resolution of our current measurement circuit is higher than our voltage measurement circuit. Overall, the system can accurately converge to the correct operating voltage and current for a wide range of solar panels and lighting conditions.

Latency: We next measure the latency of converging to the operating points on the three IV traces. We use the same set of experiments described above for the accuracy measurements. Figure 11 shows the latency of converging to an operating point in seconds. In the worst case, the SunaPlayer incurs a latency of 10 seconds to converge to an operating point from cutoff mode (0 output voltage and 0 output current). Note that this is the *absolute worst case* latency of convergence of the SunaPlayer. We show in the next section (sensitivity) that the system responds to changes in lighting conditions quickly (in less than 2 seconds)—the latency is similar to that reported in previous solar emulation platforms [5]. To understand the latency of the SunaPlayer we break down the average latency into the fraction of time spent on measuring the output voltage and current and the time taken by the state machine algorithm. The primary bottleneck of the system is in measuring the output current and voltage. It incurs close to 64% of the latency. Using a high speed instrumentation amplifier [9] and a high speed analog to digital converter will eliminate this overhead, and bring down the latency to less than 720 milliseconds.

There is also an inherent tradeoff between latency and accuracy of the SunaPlayer. Since the SunaPlayer controller uses an iterative PID-based algorithm to converge to an operating point, a larger number of iterations can lead to better accuracy at the cost of higher latency. Figure 12 explores this tradeoff and presents the result of an experiment where we measure the time taken by the SunaPlayer to converge from cutoff to an operating point. We use the Cymbet panel IV trace for the experiment and use a load impedance of 140 Ω. From the figure, we see a diminishing return trend. Moreover, depending on the accuracy that an application desires, the latency of convergence can be reduced. For example, if an application can tolerate a 20% error, the latency can be less than a second.

Sensitivity: For accurate emulation of solar cells, the SunaPlayer must be sensitive to changes in load impedance and lighting conditions. When the load impedance changes, the operating point shifts on the IV curve. When the lighting conditions change, the operating point moves to a new IV curve. Sensitivity is important when the device is deployed in the wild to power systems. For such an application, the SunaPlayer continuously senses the ambient light intensity and chooses the appropriate IV curve to emulate. To evaluate system sensitivity, we perform two experiments. In the first experiment, we select a single IV curve to emulate. We then determine the smallest change in load impedance that the SunaPlayer is sensitive to. We found that the SunaPlayer changes operating points when the load resistance changes by at least 1 Ω; hence, the system is sensitive to very small changes in load impedance. In the second experiment, we test the online mode of the SunaPlayer and sensitivity to changes in light intensity. For the experiment we select two IV traces and *assume* that they correspond to ambient indoor light intensity and dark lighting conditions. The SunaPlayer measures the ambient light intensity using the onboard light sensor and selects the appropriate IV trace. For the experiment, we set the lighting conditions to ambient lighting for one minute, then switch off the lights and set a dark light ambience for the next one minute, and then switch the lights on again. The result for the experiment is shown in Figure 13. The figure shows that the system is sensitive to changes in ambient lighting. It correctly switches from one IV trace to the other when the light intensity changes, and automatically converges to a new operating point. The time to converge to the new operating point on a different IV curve is close to two seconds, therefore, the convergence latency is low.

Portability and cost: For the online mode of operation, the SunaPlayer must be portable and should consume low power. We measured the power consumption of different

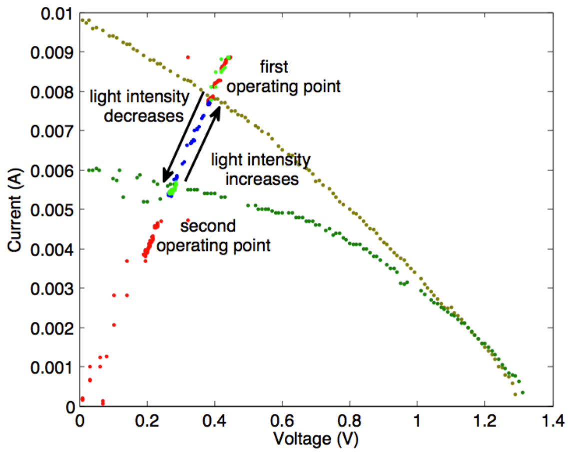


Figure 13: The figure shows that the SunaPlayer is sensitive to changes in light intensity. The red dots show the convergence of the SunaPlayer to the first operating point. A change in lighting is detected by the SunaPlayer and the blue dots show the SunaPlayer transitioning to a different IV curve. Increase in the light intensity again causes the SunaPlayer to converge to the original operating point represented by the green dots.

components of the SunaPlayer prototype when it is sourcing zero output current and voltage and V_+ is set to 6 V. The results present a baseline power consumption of the system. The power consumption of the board without the use of the LCD screen is 148 mW (24 mA). However, the bottleneck of the present prototype is the 24-bit AtoD which consumes close to 72 mA. Using a different AtoD [10], the consumption can be reduced to 5 mA. Therefore, the entire system can operate while consuming less than 30 mA when sourcing small currents, which is less than 30 times the quiescent current for a Vertex FGPA [11]. We could not compare the energy numbers with existing systems since these systems are tethered and were not designed for portable use. The embedded software on the SunaPlayer consumes only 39% program memory and 28% of the SRAM, and hence, is lightweight. Another important consideration for the SunaPlayer is its dollar cost. While an equivalent power supply [2] that provides similar range and accuracy would cost around $4000, the SunaPlayer if manufactured in quantities of 10K or above would cost less than $100 a unit—an order of magnitude lower cost.

6. RELATED WORK

The SunaPlayer builds on previous work on emulation platforms for solar panels and batteries, and complements a suite of research efforts on renewable energy driven systems.

Emulators: There are several prior efforts on designing emulation hardware for batteries and solar cells. B# [12] is a battery emulator that uses an adjustable linear regulator to emulate output battery voltages. The operating range of the emulator is 1.0–4.5V, and the system can source a maximum current of 800mA. S# [5] uses the same architecture as B#, and extends the approach to solar panel emulation. B# reads the current draw of the system and looks up the corresponding voltage using a lookup table, and generates a control signal at the output of a digital to analog converter. While using a linear regulator simplifies the design of the control logic, it suffers from the drawbacks described in §3—a voltage regulator is a linear device that is not sensitive for wide ranges of output voltages and currents. Ekho [1] is a solar cell emulator tuned to small currents. Ekho uses a simple design where the load is powered by a capacitor. Hence, the voltage drop across the load can be measured using the voltage drop across the capacitor, and consequently, the corresponding operating point on the IV curve (voltage and current) can be calculated. The system uses a FPGA to speed up the IV calculations. While the system has high accuracy, its operation relies on the existence of a constant voltage source to power the load. The system similar to the SunaPlayer is the National Instrument's programmable power supply [2] that is capable of simulating solar panels with a wide range of operation. The power supply offers fine grained measurement resolution similar to our measurement circuit. However, the programmable power supply is a closed source system and the design is not available to the research community. Additionally, the programmable supply costs several thousands of dollar ($4,000–$5,000) and is not a portable device. In addition to emulators, simulators have also been designed for mote-class devices [13, 14, 15, 16] and micro-harvesters [17, 18]. The simulation platforms use analytical models that are often inaccurate since they do not account for a wide variety of ambient and environmental conditions that effect the power generated. Our work also builds on research in the 1980s that use bipolar junction darlington transistor chains for profiling solar panels [19] and the use of power transistors for conditioning the output of solar panels deployed in residential settings [20]. Solar panel profiling is used to generate IV curves for solar cells and benchmark the performance of solar panels. Signal conditioning circuits are used to reduce noise. The goal in this paper is to use the BJT darlington chain for a different purpose: emulating solar cells. However, it is possible to augment our system with the system presented in [19]. The solar profiler could generate the IV curve that the SunaPlayer can emulate. While in our system, noise was not a primary bottleneck, the circuit presented in [20] could be used for signal conditioning if the SunaPlayer supports wider current-voltage ranges.

Renewable energy driven systems: There is a plethora of research related to renewable energy driven systems. These include medium scale systems for environmental sensing [21, 22], networking [23], large scale systems for renewable energy driven homes [24], and micro-harvester systems for indoor environment monitoring [25]. The number of renewable energy driven devices have grown in the past with the goal to create an energy-independent society. There has been a focus on building harvesters for renewable energy driven devices [26], adaptive algorithms that balance energy demand with supply [27], and hardware platforms and programming paradigms that minimize the power consumption of devices [23]. The SunaPlayer is complementary to these renewable energy driven devices. It can be used in evaluating and debugging these devices without deploying them in the wild. Moreover, it can help in evaluating the devices under a wide range of environmental conditions.

7. DISCUSSIONS

In this section, we discuss limitations and improvements that can be made to the SunaPlayer prototype.

7.1 Evaluation on non-resistive loads

The evaluation presented in this paper was performed with a variable resistive load. Resistive loads have a single current component with a proportional dependence on voltage. In contrast, common CMOS load models predict a combination of constant and linearly-dependent supply current components, which is actually easier to regulate. However, modern systems can be complex, and may even incorporate dynamic supply-voltage dependent behaviors. Analytical models for every such complex system are infeasible to produce. Luckily, power distribution subsystems for these devices typically employ batteries and supply filtering to smooth rapid supply transients. It is important that our system respond quickly enough to go unnoticed to such systems. We foresee testing the SunaPlayer with such devices and estimating the overall system sensitivity to parameters though experimental parameter perturbations. Any parameters modifications which result in dynamics significantly varied from that predicted by simpler approximate models may be investigated further. However, we do believe that the system is designed to handle these loads. For instance, the PID controller is an iterative algorithm that has been shown to model non-linear control systems well. Secondly, the system handles a non-linear load using pairwise linear functions in the `PID_low` state, hence, the convergence accuracy for the SunaPlayer should be similar to resistive loads at the cost of longer convergence latency.

7.2 Thermal properties

One of the side effects of a wide operating range is accounting for heat dissipation of different components. For instance, the gain of the darlington changes logarithmically with increase in temperature. While a processor fan provides a temporary remedy, a surface mount heat sink attached to the junctions of the darlington is a more robust solution. Similarly heat sinks are required for the sense resistor and power supply modules.

7.3 High speed components

A primary latency and energy bottleneck is the speed of the analog-to-digital converter (ADC) and the instrumentation amplifier (INA). The present prototype does not support high speed measurements of the output current and voltage. By replacing the present AtoD and INA chips with high speed ICs, the system can be made more power and latency efficient.

7.4 Wider range of operation

While the SunaPlayer supports a wide range of operation, this range can be further extended with changes to the circuit. The darlington is capable of sourcing up to 20V output and several amps of current. However, the hardware bottleneck of the system is the linear regulator used to set V_+. Our present IC supports a maximum of 10V; hence, limiting the maximum output voltage to 9.8V at low currents. By replacing the linear regulator with a wide range one can improve the range. Moreover, using a higher resolution digital potentiometer that controls the linear regulator can help fine grained control of V_+.

8. CONCLUSION

In this paper, we present the design, implementation, and evaluation of the SunaPlayer, an emulation platform for solar panels. The SunaPlayer uses a high gain analog device, a PNP darlington transistor as the current source that scales better for wider range, and a multi-resolution driving and measurement circuit to control the darlington. It uses a sophisticated state machine based PID controller that converges to an operating point on a solar cell's IV curve with high accuracy while incurring short latency. The SunaPlayer can emulate a wide range of solar panels under a range of lighting conditions, can source output voltages from 0.02V to 9.8V, currents from 430 micro-amps to 1.89 amps, and can power arbitrary loads such as a combination of storage devices, charge controllers, and sensing systems.

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