International Journal of Smart Grid and Clean Energy

Energy management for solar-powered IoT devices with performance adjustment

YongSeok Lee, Moonju Park *

Department of Computer Science and Engineering, Incheon National University, Incheon 22012, Korea

Abstract

In this paper, we propose a power management framework for solar-powered Internet of Things (IoT) devices to maximize the lifetime of the system by adaptively changing performance of the system. Our framework balances the energy consumption and the performance of the IoT system by monitoring energy accumulation and battery, and ensures the minimum level of service. The framework has been implemented in real hardware and software. Experiments with the implemented system shows that our framework can help increase the lifetime of the solar powered IoT system. The framework prevented the IoT device from power down due to the full discharge of the battery at night time, by changing the execution rate based on energy accumulation and battery status. The proposed framework has been implemented using open hardware compatible with Arduino, so it can be used for a wide range of IoT applications and services.

Keywords: Solar power, Embedded system, Low power, Energy management, IoT

1. Introduction

Technology advances in low-power, small form factor, and high-performance embedded systems enabled the use of Internet of Things (IoT) in many applications such as motor industry, electrical appliance, medical, military, traffic environment, and so on. Typical IoT devices have limited power sources like batteries that restrict the performance and the lifetime of the devices. To overcome the problem, use of renewable energy, including solar power, has been considered as a promising energy source of IoT devices. Especially when the IoT devices are used outdoors, solar power solutions can be adopted as an efficient energy supplier, considering their decreasing cost and increasing solar cell efficiency. Solar-powered systems also have advantages over battery-only systems which require maintenance and replacement of batteries.

Solar power systems must cope with the uncertainties in energy supply because we cannot control the amount of energy gathered from fixed size solar panels that depends on the environmental and the atmospheric conditions such as season of the year and clouds in a day. On the other hand, IoT services must provide high availability which requires stable and predictable energy supply. For this reason, an IoT service such as wireless camera monitoring must address the trade-off between meeting performance requirements and maximizing lifetime [1,2]. To cope with the uncertainty, batteries are often used as an energy buffer to endure the fluctuation in energy supply from the solar panel. When the amount of energy generated from the photovoltaic cells is enough to operate the IoT node, excessive energy accumulated from the solar panel is stored in batteries. The stored electric energy will be used when the solar power is not available (e.g., at night), or the amount of generated power is not enough to operate the device because of the weather condition.

However, the use of batteries again introduces the maintenance problem, diminishing the advantage of

* Manuscript received October 30, 2018; revised December 6, 2018.
Corresponding author. Tel.: +82-32-835-8556; *E-mail address*: mpark@inu.ac.kr.
doi: 10.12720/sgce.8.1.22-30

solar power system. The battery is ageing and high/low temperature can cause reduction in the amount of electrical capacity of batteries that eventually requires their replacement. Battery lifetime and capacity is affected by many parameters. Charging-discharging cycle ages the battery, resulting in reduced capacity and lower charging efficiency, while temperature may cause multiple effects on the battery [3]. In extreme cold weather below -20℃, the charging capacity of Li-ion battery drastically drops [4]. IoT systems that are designed to be solar-powered can be presumed to be used outdoors, and in such environments, changes in temperature could be very high especially in the populated northern hemisphere. Also, regarding the uncertainty of the solar energy accumulation, more frequent discharging of batteries in the solar-powered IoT systems should be assumed. Thus, to make the use of solar power in IoT systems feasible, we need to provide a solution to prolong the lifetime of the battery while guaranteeing the operation of the IoT devices simultaneously. It can only be achieved by controlling the performance of the IoT system to manage the power consumption of the system to prevent complete discharge of the battery, while still achieving satisfactory service from the IoT system.

In this paper, we propose a power management framework for solar-powered IoT devices to maximize the operation lifetime of the system by adaptive performance adjustment. Our framework balances the energy consumption and the performance of the IoT system by monitoring energy accumulation and battery status to use the information for changing the execution rate dynamically. The framework has been implemented in real hardware and software. Experiments with the implemented system shows that our framework can help increase the lifetime of the solar powered IoT system.

The remainder of this paper is organized as follows. In Section 2, we discuss the related works in power management for solar powered IoT systems. In Section 3, our framework for energy management system for solar powered IoT devices is described, the details of our implementation of the energy management framework are provided. In Section 4, experimental results are presented. Finally, Section 5 concludes our work.

2. Related Works

A framework called QuARES (quality-aware renewable energy-driven sensing framework) was proposed in [5] to manage performance of solar-powered embedded systems based on solar energy prediction. They introduced the concept of QoS (Quality-of-Service) in managing the performance. The QoS levels the system supports should be determined off-line using the solar energy prediction data due to the high complexity of their algorithm. Based on the QuARES framework, a power management for a camera sensor network by utilizing hybrid power sources, super-capacitor and Li-ion battery, has been presented [6]. They focused on sustainability in energy supply to solar-powered embedded system. Maximizing the lifetime of devices with renewable power sources in WSN (Wireless Sensor Network) by balancing the power and the performance has been discussed in [7]. A recent real implementation of solar-powered video monitoring system using wireless IoT devices is reported in [1], but power management is not supported.

Embedded systems in IoT devices usually have real-time requirements such as execution rate or limited margin in response time. Real-time scheduling techniques for such embedded systems powered by sustainable energy sources, including solar energy, have been studied. In the case of the uniprocessor, it Earliest Deadline First (EDF) scheduling has been shown as an optimal on-line algorithm for real-time systems in energy harvesting computing system with unpredictable energy supply [8]. An EDF-based scheduling algorithm has been proposed in [9] with a periodic real-time scheduling for energy harvesting real-time systems. Adoption of weakly hard real-time system for energy-awareness has been proposed that allows intermittently skipping a job when the system is short of energy [10]. The adoption of weakly hard real-time system introduced the concept of QoS in designing IoT systems for balancing service levels (performance) and energy usage. Using the weakly real-time system, a QoS level management framework has been proposed for solar powered embedded systems to maximize the minimum QoS level while minimizing the energy usage in [11]. In [12], an optimal approach by maximizing the sum of the QoS levels achieved at each hour was presented.

3. Energy Management Framework for Solar Powered System

3.1. Hardware architecture and power system

The hardware of the solar powered IoT device and energy supply is organized as illustrated in Fig. 1. The IoT node is built using the Arduino 101 [12] equipped with Intel Curie module which has Intel Quark SE (synthetic environment) core and ARC EM4 DSP (digital signal processor) that is compatible with Arduino Uno. The node also has a Bluetooth module which we use as a primary communication method between the node and the server for low power consumption and a camera module. We assume the situation where IoT devices are used as camera sensors in outdoor video monitoring as in [1]. The node's camera is an Arduino-compatible device, ArduCam mini OV2640 [13], of 2 mega pixels resolution that produces 6 MB of raw data for a captured image. The camera module can be set to the low power mode when it is not activated. Because the Bluetooth module supports 25 Mbps of data transfer speed at maximum, it is expected to send a camera-captured image in 1.92 seconds. It actually takes about 2 seconds to take a picture and send it to the server because of the overhead of camera operations, including activation, focusing, taking a photo, and deactivation.

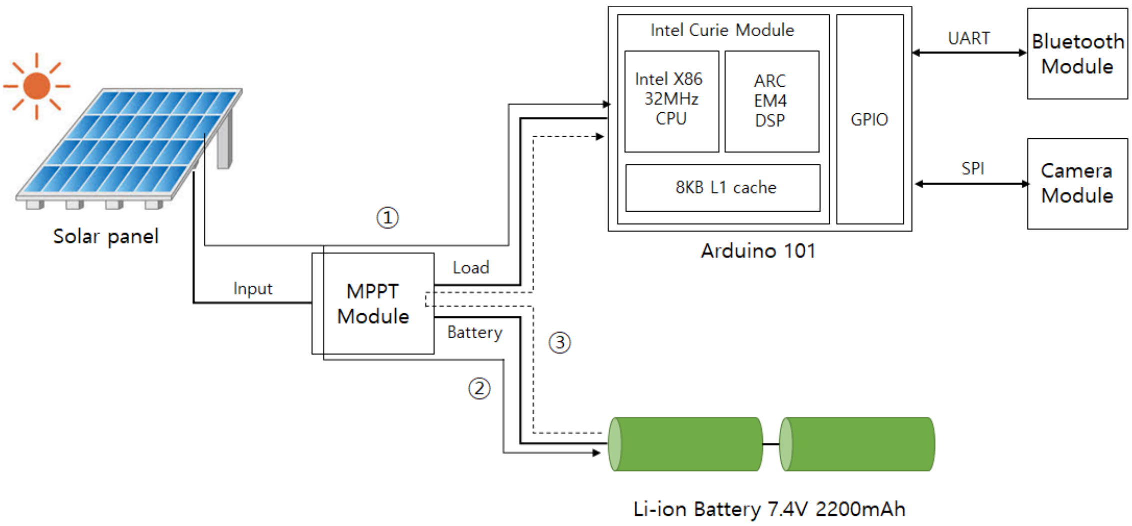

Fig. 1. Hardware architecture

The IoT node's power is supplied from the solar panel when the weather permits. An MPPT (Maximum Power Point Tracking) module is used to maximize power extraction from the photovoltaic cells. The batteries and the node are both connected to the MPPT module. When the sun is up, the solar panel generates power enough to operate the node; the node is powered by the solar power only (line ① in Fig. 3), and surplus power is stored in the batteries (line ②). When solar power is not available (e.g., at night), the node is powered from the batteries (line ③) which are charged in the daytime.

Because detailed solar radiation data at Incheon, where the research has been conducted, is not available, we had to measure the level of solar radiation with a sufficiently large solar panel. According to the data from the New & Renewable Data Center of KIER (Korean Institute of Energy Research), at Seoul (the capital city of Korea near Incheon), the average amount of energy accumulated over 1㎡ per day in winter (from December to February) is 1.97 kWh ~ 3.01 kWh [14]. Because the energy produced by photovoltaic (PV) cells is directly proportional to the panel area and efficiency of the PV cells, the energy output from the panel is given by the following [1].

Energy Output = Solar radiation energy × Panel area × Efficiency

The solar panel we use has wafer-based crystalline silicon cells with 17.25% efficiency, and the IoT node consumes about 1.136 Wh for capturing and sending an image at full rate which results in 27.264 Wh of energy needed for a whole day operation. Assuming the worst-case solar radiation (1.97 kWh), the panel area needs to be larger than about 0.08 ㎡, or 800 ㎠. Hence, we selected a solar panel of size 285 mm by 295 mm (840.75 ㎠). Fig. 2 shows exemplary data of energy output from the solar panel, accumulated over an hour (the energy is shown in Joule). On a sunny day in winter, the panel generates 10 Wh at peak, but nothing for almost 13 hours between 18:00 and 7:00.

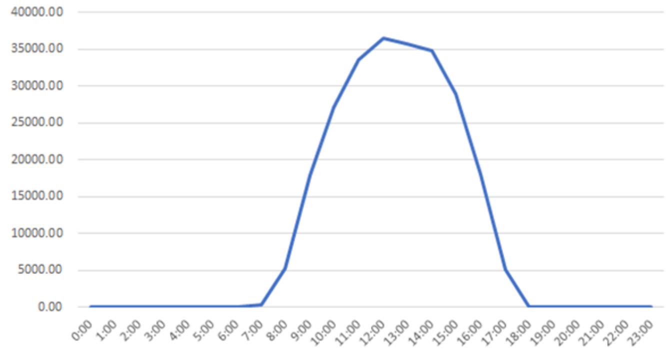

Fig. 2. Energy generated on 3 Feb. 2018 (in Joule)

Although the total amount of the energy accumulated in the solar panel is enough to operate the target IoT system for 24 hours, we need to resolve the problem of irregularity in energy supply from the panel. Batteries can be used to store the excessive amount of solar energy during daytime and the energy can be used after sunset. The amount of total energy that can be accumulated during a day is as much as about 67.5 Wh. Considering the loss of energy in charging an ordinary Li-ion battery is about 10%, and 27.264 Wh is used by the IoT system for day, about 33.486 Wh can be accounted for excessive energy generated by the solar panel. Because the supply voltage required by the IoT device is 7.4 V, two 3.7 V 4525 mAh Li-ion battery packs are needed to store the total excessive energy. But seamless operation of the IoT system even at night can be ensured with smaller capacity, if we carefully manage the power consumption. Batteries are only needed to hold energy enough for night time (about 13 hours) for which only 14.768 Wh amount of energy is required. Considering 10% loss, two 3.7 V 2218 mAh batteries can hold the same amount of energy. Thus, we chose a 3.7 V 2200 mAh pack of Li-ion batteries available in the market. The status of the batteries is monitored using a voltage sensor connected to the IoT device.

3.2. Energy management framework

We propose a control framework for energy management in solar-powered IoT system to achieve longer lifetime while providing a certain level of performance guarantee. To cope with the problem of uncertainty in solar energy accumulation, we use the forecast data for initial planning. A server communicates with the IoT system to provide prediction data of the solar energy once a day. The IoT system adjusts the performance of the IoT device based on the prediction data. Online adaptation should be performed in the framework to compensate for the difference between the predicted data and the real energy generated from the panel. Fig. 3 shows the framework applied to an example camera sensing system.

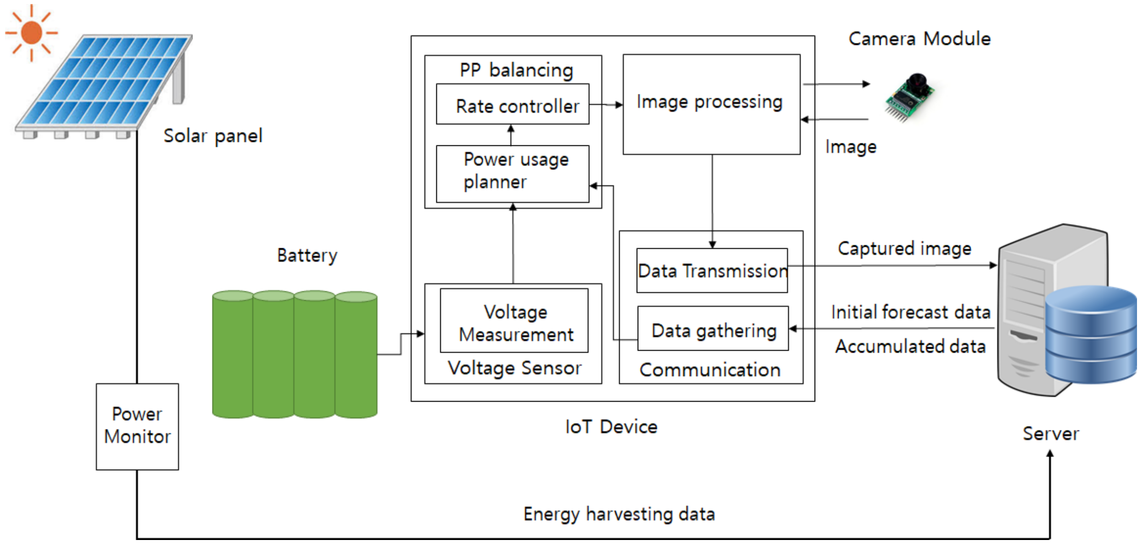

Fig. 3. Energy management framework for a solar-powered IoT

Our framework consists of mainly four parts: monitoring, sensing, control, and communication. The monitoring part (power monitor and voltage sensor in Fig. 3) monitors the energy accumulated from the solar panel which is sent to a server where the data is processed and then fed to the IoT system. The IoT system monitors the status of the battery (voltage level). Based on the monitoring data of the harvested solar energy and the battery status, the power usage planner in the control part (PP balancing in Fig. 3) determines the execution rate of the sensing part and how the energy should be used. Then the rate controller controls the sensing part (camera module in Fig. 3) to be executed at the rate determined by the power usage planner. The sensed data (camera image in this case) is gathered and transmitted to the server by the communication part.

In our exemplary implementation of the framework, the execution rate is defined as the number of shots in a given time. To relate the execution rate with the energy consumption, we have measured the actual energy required to perform camera sending and sending data at each sensing rate. Because it takes about 2 seconds in taking a photo and sending it, the maximum sensing rate is 5 takes/10 seconds. We define 5 levels of performance for the IoT system, from 1 takes/10 seconds to 5 takes/10 seconds. Fig. 4 shows the energy consumption in Joule for each performance level. Raising one performance level requires about 100 J.

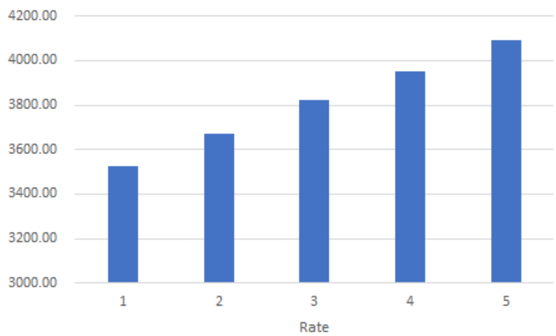

Fig. 4. Energy consumption in Joule for different operation rate (takes per 10 seconds)

The power usage planner determines the performance level of the next time slot, based on the difference between the predicted energy and the monitored energy versus the current battery status.

Because the times of sunrise and sunset are already known for a specific date, we can estimate how much energy will be needed for the IoT system to operate at a certain level of performance. The initial planning is done by the server and sent to the IoT system once a day. The power usage planner adjusts the performance level if the monitored solar power accumulation differs from the prediction. Fig. 5 shows the algorithm for updating the performance levels.

Determine_next_rate

Input: prediction[], performance_levels[], cur_slot, EH, battery_energy
Output: performance_levels[]

```
next_slot := cur_slot + 1

if EH > EC[max_level] then
   performance_level[next_slot] :== max_level
else
   slots := next_sun_rise – cur_slot
   diff := prediction[cur_slot] – EH
   avail := battery_energy/slots

   if avail < EC[min_level] then
      performance_level[next_slot] := min_level
   else
      performance_level[next_slot] := performance_level[next_slot] + ⌊diff / level_diff⌋
   endif
endif
```

Fig. 5. Power usage planner algorithm

EH is the solar energy accumulated in the current slot, and EC[level] represents the energy consumption required for a performance level. We assume that the difference in energy requirement between two adjacent levels is given by *level_diff*. If the solar energy is adequate to supply power to the IoT system in full rate, the system can run at the highest performance level without using the energy stored in the battery so that we can change the performance level to the max. Otherwise, we need to check the battery status to determine the performance level. If the average battery energy that can be used for each time slot is lower than the minimum required energy for the IoT system, the performance level remains at the minimum. If there is some amount of energy in the battery available for higher level of performance, we adjust the next performance level by examining how much error is made from the prediction.

4. Experimental Results

The energy management framework has been implemented and tested to see how it balances the performance and energy consumption to prolong the lifetime of the IoT system. For comparison, we also tested the IoT device without power management, which runs at the maximum rate of execution (5 takes per 10 seconds). Fig. 6 shows the energy consumption in Joule of the board in the IoT system and energy supply from the solar panel for two days. The solar panel can generate more energy from 11:00 to 17:00, but power is not drawn from the panel because the battery is already full. The energy consumption in the board came down to zero from 5:00 to 7:00, because the device was powered down from 4:15 until 8:29 given that the battery was discharged (see Fig. 7). The voltage levels of the battery are shown in Fig. 8

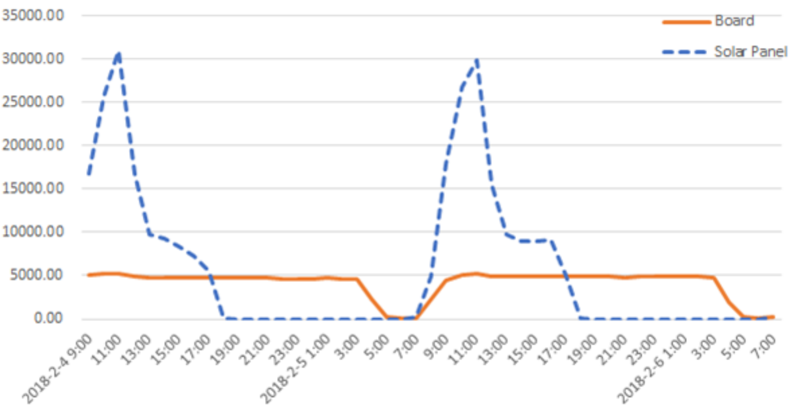

Fig. 6. Energy output from the solar panel and the energy consumption of the IoT node without power control

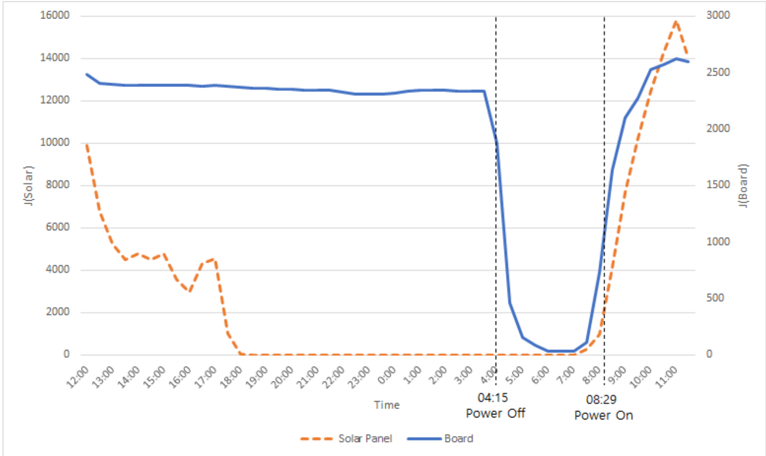

Fig. 7. Power down due to battery discharge

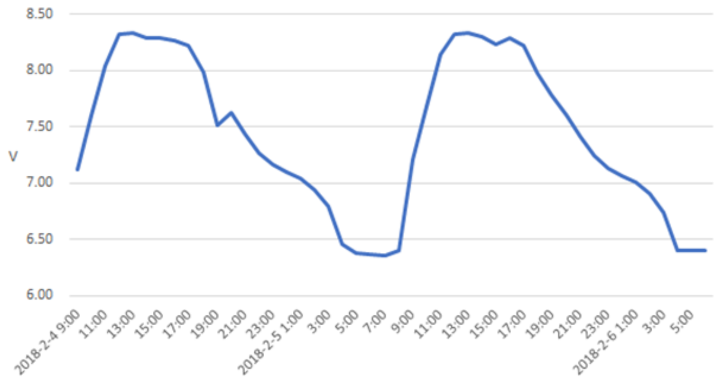

Fig. 8. Voltage level changes of the batteries in full rate mode

The energy generation and consumption when our framework is employed for managing the performance, and the power consumption is shown in Fig. 9. As shown in the figure, the energy consumption of the IoT device started to drop at about 17:00, when the accumulated solar energy becomes below the maximum energy consumption level. The performance level goes down while there is no power generated from the solar panel, then it goes up as the solar power becomes available.

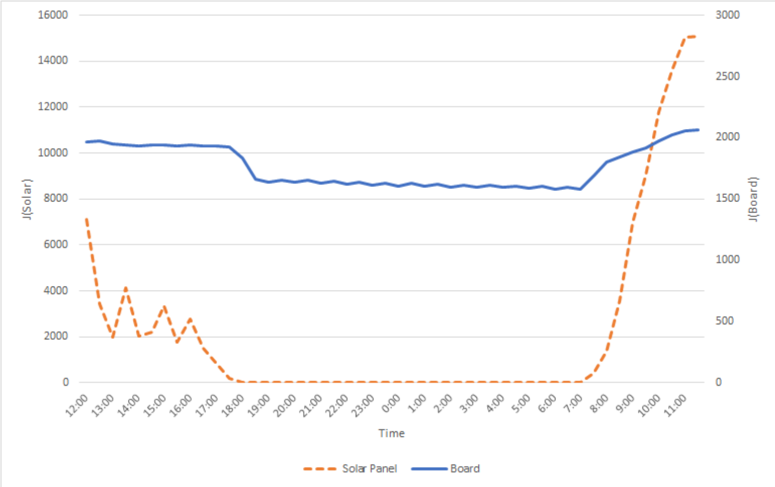

Fig. 9. Voltage level changes of the batteries in full rate mode

We can see that there is no power down in Fig. 9 because the IoT device was controlled to run at a lower performance level when it uses the energy stored in the battery. It prevents the battery from fully being discharged, which will prolong the battery lifetime, as well as the IoT system's service time.

5. Conclusion

In this paper, we have proposed a framework for power management and performance control to deal with the unsustainable energy supply in the solar-powered IoT devices. Our framework provides a guarantee to ensure the minimum level of service while prolonging the lifetime of the battery as well as the system by balancing the performance and the power consumption of the device. The implemented system was tested in a real environment. The framework prevented the IoT device from power down due to the full discharge of the battery at night time by adaptively changing the execution rate based on energy accumulation and battery status. The proposed framework has been implemented using open hardware compatible with Arduino, so it can be used for a wide range of IoT applications and services.

Acknowledgements

This work was supported by Incheon National University Research Fund in 2018.

References

[1] Abas K, Obraczka K, Miller L. Solar-powered, wireless smart camera networks: An IoT solution for outdoor video monitoring, *Computer Communicaitons*, 2018.

[2] Pinto A, Zhang Z, Dong X, Velipaslar S, Vuran MC, Gursoy MC. Analysis of the accuracy-latency-energy tradeoff for wireless embedded camera networks, In: *Proc. of Wireless Communicaitons and Networking Conference*, 2011:2101-2106.

[3] Vetter J, Novák P, Wagner MR, Veit C, Mőller KC, Besenhard JO, Winter M, Wohlfahrt-Mehrens M, Volger C, Hammouche A. Ageing mechanisms in lithium-ion batteries. *Journal of Power Sources*, 2005; 147:269-281.

[4] Chin KB, Smart MC, Brandon EJ, Bolotin GS, Palmer NK, Katz S, Flynn JA. Li-ion battery and supercapacitor Hybrid energy system for low temperature Smallsat applications, In: *Proc. of 28th Annual AIAA/USU Conference on Small Satellites*, 2014

[5] Dang N, Bozorgzadeh E, Venkatasubramanian N. QuARES: Quality-aware data collection in energy harvesting sensor networks, In: *Proc. of International Green Computing Conference and Workshops*, 2011:1-9

[6] Dang N, Ghaderi Z, Park M, Bozorgzadeh E. Harvesting-aware adaptive energy management in solar-powered embedded systems, In: *Proc. of 17th International Symposium on Quality Electronic Design*, 2016:331-337

[7] Seah WKG, Eu ZA, Tan HP. Wireless sensor networks powered by ambient energy harvesting (WSN-HEAP)–Survey and challenges, In: *Proc. of Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic*

Systems Technology, 2009:1-5.

[8] Chetto M. Optimal Scheduling for real-time jobs in energy harvesting computing systems. *IEEE Transactions on Energing Topics in Computing*, 2014:122-133

[9] EL. H, Ghor M. Chetto RH. Chehade. A real-time scheduling framework for embedded systems with environmental energy harvesting, *Computer & Electrical Engineering*, 2011; 37(4):498-510

[10] Niu L, Quan G. Peripheral-conscious energy-efficient scheduling for weakly hard real-time systems. *International Journal of Embedded Systems*, 2015:11-25

[11] Kooti H, Dang N, Mishra E, Bozorgzadeh E. Energy budget management for energy harvesting embedded systems, In: *Proc. of IEEE International Conference on Embedded and Real-Time Computing Systems and Applications*, 2012:320-329

[12] Dang N, Valentini R, Bozorgzadeh E, Levorato M, Venkatasugramanian N. A unified stochastic model for energy management in solar-powered embedded systems, *International Conference on Computer-Aided Design*, 2015:621-626

[13] Arduino 101, 2018, [Online]. Available: https://ark.intel.com/products/92347/Arduino-101

[14] ArduCam OV2640, 2018, [Online]. Available: http://www.arducam.com/camera-modules/2 mp-ov2640/

[15] New & Renewable Energy Data Center, Korea Institute of Energy Research, 2018. http://kredc.kier.re.kr