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A survey of hybrid solar-wind energy harvesting for embedded applications

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***Abstract*-To enable off-grid deployments of autonomous systems for extended operational durations, robust energy harvesting in the medium power range (1–10 W) is essential. supercapacitor-based solar energy harvesters have emerged as a popular alternative due to their long lifetime under repeated charge-discharge cycles, low maintenance, environmental friendliness, and energy predictability and scalability. despite their advantages, such systems are not well matched with applications that require power continuously over their operational lifetime because solar power is unavailable during nights and severely reduced on cloudy days. for such applications, it is beneficial to combine solar power with another power source—such as wind—that exhibits complementary availability. In this paper, we present multiple solar/wind (hybrid) supercapacitor-based harvesters, leveraging existing open-source solar-only harvester designs. our designs center around three main categories that i) add wind harvesting capability to create a wind-only harvesting system, ii) use multiple harvesters for utilizing hybrid sources of power and for providing fault tolerance, or iii) use a single harvester in a time multiplexed configuration to simultaneously harvest from multiple power sources. We provide extensive experimental results to document the functionality and operational performance of a representative set of these designs.**

***Keywords*-multiple solar/wind (hybrid) supercapacitor-based harvesters, leveraging existing open-source solar-only harvester designs**

I INTRODUCTION

Autonomously deployed embedded systems in the medium power (1–10 W) range have recently received broad attention in the literature due to their applications in numerous emerging technologies, including smart cities, environmental monitoring, agriculture, and emergency management.These applications typically employ a network of field systems in locations with no or limited power infrastructure, requiring them to incorporate an autonomous ambient power harvesting solution for a seamless operation.The appropriate energy harvesting approach for an embedded field-deployed system is primarily determined by the power requirements of the target applications. These requirements along with the most commonly harvested ambient power sources are categorized and compared. While embedded systems that operate in the (1 nW–10 mW) power range can be powered from piezoelectric, thermal, microbial, RF, wind, and solar energy harvesters, medium-power embedded systems that operate in the (1–10 W) power range rely primarily on solar, wind, or a combination of solar and wind (hybrid) energy harvesters. A rich body of energy harvester designs exists in the literature that accepts solaronly, wind-only, or hybrid solar/wind power inputs and buffer the harvested energy in the rechargeable batteries.

Autonomous solar-only—or wind-only—field systems are susceptible to frequent power interruptions (downtime), because neither solar panels nor wind turbines can individually provide continuous power throughout an entire day. Solutions introduced in the literature alleviate the deficiency of these power sources by buffering the surplus portion of the harvested energy in a large energy buffer such as rechargeable batteries, or supercapacitors. When there is inadequate input power to feed the embedded system (e.g., dark nights or days with no wind), the buffered energy is retrieved to compensate for the shortage. However, if the input power is below the power consumption of the system for an extended period, the buffered energy is eventually depleted, causing a system outage and increasing the downtime.

Hybrid harvesters that can utilize both solar or wind power are attractive because these two sources often have complementary availability. This means that they can meet desired downtime targets without requiring over-provisioning of buffer and panel/turbine resources; an example of this is illustrated, which depicts the average solar irradiation level and wind speed in the Rochester, NY region over the 2009–2010 calendar years. While the solar power availability peaks between the months of April through August, wind power is the lowest during this period; outside this period, an inverse pattern is observed. In the presence of such complementarity, a hybrid harvester—powered from both solar and wind sources—is expected to provide a much steadier power output as compared to one that has a single power source.

Embedded systems powered by solar/wind harvesting are subject to cyclical and variable availability of power, which implies frequent charge-discharge cycles for the energy buffer used. Supercapacitors are particularly attractive as an energy buffer in these systems because of their much longer lifetime under repeated charging and discharging. The lower energy densityof supercapacitors compared with batteries, however, makes their physical size a critical issue in deployments and this has hindered the adoption of supercapacitors despite their favorable characteristics such as environmental-friendliness, convenient power management, energy predictability, and longer lifetime.Because hybrid harvesting can reduce the required energy buffering capacity, supercapacitors can be immediate beneficiaries of hybrid solar/wind harvesters. In this paper, we propose multiple supercapacitor-based hybrid wind/solar energy harvesters.

Our designs are based on the UR-SolarCap solaronlyopen-source energy harvester,which was not originally designed to harvest wind power. As the first step of our design, we introduce the required hardware and software adaptations to convert UR-SolarCap to a wind-onlyharvesting system. As the next step, we propose multiple topologies to implement a hybrid(wind/solar) harvesting system using one or more UR-SolarCap boards. Our last step introduces a design variant that harvests multiple power sources using a single UR-SolarCap; for this design, an analog time multiplexing mechanism is introduced that buffers and harvests individual sources in discrete time intervals, thereby reducing the component count substantially to provide a lower-cost harvester alternative.

II.RELATED WORKS

2.1 “Real-Time Video Based Highway Traffic Measurement and Performance Monitoring”,[1]

This paper presents a real-time highway monitoring system for tracking and classification of vehicles with the computation of traffic flow parameters from live video streams. The proposed system robustly detects and tracks vehicles during daylight hours and accurately classifies them into 8 different types by leveraging tracking information. The system is able to process video continuously over long time periods, accumulating large volumes of tracking data to build daily highway models consisting of the traffic flow parameters, density, flow, and speed. These daily models are used to categorize the speed profile of live traffic.

2.2 “Intelligent Transportation Spaces: Vehicles, Traffic, Communications, and Beyond”,[2]

Recent years have witnessed numerous technical breakthroughs in electronics, computing, sensing, robotics, control, signal processing, and communications. These have significantly advanced the state of applications of intelligent transportation systems. More recently, as one leading effort toward the cyber-physical-social system, the concept of intelligent transportation spaces was proposed to further improve the vehicles, traffic, and transportation safety, efficiency and sustainability. ITSp integrate not only various ITS modules, but also pedestrians, vehicles, roadside infrastructures, traffic management centers, sensors, and satellites. With distributed and pervasive intelligence, ITSp clearly impose some stringent requirements on the information exchange among all entities within the ITSp, in terms of the information availability, reliability, fidelity, and timeliness. These requirements, together with the high mobility of vehicles and the highly variable network topology, make the communications and networking for ITSp very challenging. This article will introduce the concept of ITSp and analyze possible communication technology candidates for ITSp. Further discussions will also be provided at the end of this article.

2.3 "Internet of Things for Smart Cities",[3]

The Internet of Things (IoT) shall be able to incorporate transparently and seamlessly a large number of different and heterogeneous end systems, while providing open access to selected subsets of data for the development of a plethora of digital services. Building a general architecture for the IoT is hence a very complex task, mainly because of the extremely large variety of devices, link layer technologies, and services that may be involved in such a system. In this paper, we focus specifically to an urban IoT system that, while still being quite a broad category, are characterized by their specific application domain. Urban IoTs, in fact, are designed to support the Smart City vision, which aims at exploiting the most advanced communication technologies to support added-value services for the administration of the city and for the citizens. This paper hence provides a comprehensive survey of the enabling technologies, protocols, and architecture for an urban IoT. Furthermore, the paper will present and discuss the technical solutions and best-practice guidelines adopted in the Padova Smart City project, a proof-of-concept deployment of an IoT island in the city of Padova, Italy, performed in collaboration with the city municipality.

2.4 "Large Scale Distributed Dedicated- and Non-Dedicated Smart City Sensing Systems",[4]

The past decade has witnessed an explosion of interest in smart cities in which a set of applications such as smart healthcare, smart lighting, and smart transportation promise to drastically improve the quality and efficiency of these services. The skeleton of these applications is formed by a network of distributed sensors that captures data, pre-processes, and transmits it to a center for further processing. While these sensors are generally perceived to be a wireless network of sensing devices that are deployed permanently as part of an application, the emerging mobile crowd-sensing (MCS) concept prescribes a drastically different platform for sensing; a network of smartphones, owned by a volunteer crowd, can capture, preprocess, and transmit the data to the same center. We call these two forms of sensors dedicated and non-dedicated sensors in this paper. While dedicated sensors imply higher deployment and maintenance costs, the MCS concept also has known implementation challenges, such as incentivizing the crowd and ensuring the trustworthiness of the captured data, and covering a wide sensing area. Due to the pros/cons of each option, the decision as to which one is better becomes a non-trivial answer. In this paper, we conduct a thorough study of both types of sensors and draw conclusions about which one becomes a favorable option based on a given application platform.

2.5 "Design and Deployment of a Sustainable Sensor Network for Wildlife Monitoring",[5]

The increasing adoption of wireless sensor network technology in a variety of applications, from agricultural to volcanic monitoring, has demonstrated their ability to gather data with unprecedented sensing capabilities and deliver it to a remote user. However, a key issue remains how to maintain these sensor network deployments over increasingly prolonged deployments. In this article, we present the challenges that were faced in maintaining continual operation of an automated wildlife monitoring system over a one-year period. This system analyzed the social colocation patterns of European badgers

(Meles meles) residing in a dense woodland environment using a hybrid RFID-WSN approach. We describe the stages of the evolutionary development, from implementation, deployment, and testing, to various iterations of software optimization, followed by hardware enhancements, which in turn triggered the need for further software optimization. We highlight the main lessons learned: the need to factor in the maintenance costs while designing the system; to consider carefully software and hardware interactions; the importance of rapid prototyping for initial deployment (this was key to our success); and the need for continuous interaction with domain scientists which allows for unexpected optimizations.

2.6 "Smart field monitoring: An application of Cyber-physical Systems in Agriculture",[6]

A huge amount of grain and food is lost to pests and particularly rats, and environmental is contaminated using pesticides. For rodent's control there has been no systematic high-tech solution until now. We aim to develop a "Smart Pest Control" Solution (SPeC) particularly a "Rat Detection System" (RDS) in order to provide a infrastructure for monitoring rats in the agricultural field. We believe this system can help pest control experts in reducing tremendous costs for rats control as well as huge amount of crop waste and environment contamination. We will propose our solution based on Cyber Physical Systems(CPSs) and will elucidate enabling technologies and frontiers for this research.

2.7 "Smart City Sensing and Communication Sub-Infrastructure",[7]

Significant recent research activities and initiatives by local governments to establish resilient smart city infrastructures signal that time is right for smart cities in the near future. For example, sensors deployed within a city could monitor traffic patterns, perform environmental measurements and determine optimum traffic routing, when deployed in areas that have a power infrastructure. In this paper, we conceptualize the deployment of such nodes, which we term Smart Boxes, in a part of the city where there is no existing or currently functional energy and communication infrastructure. We envision our proposed smart boxes incorporating a multi-source energy harvester (e. g., wind/solar). Eliminating the infrastructure requirement allows our smart box to act as an emergency cell phone network in any part of the city, thereby forming an emergency sub infrastructure. To improve scalability, we use a Software Defined Radio (SDR) within the box. The contribution of this paper is to provide an architectural map of the box and a proof-of-concept experimental demonstration of its LTE network capabilities. Our experiments show that the box is capable of serving three cellular users and can be powered from a 50–100 W solar panel and a 50-100 W wind turbine, thereby confirming its feasibility as a Smart City node.

2.8 "Fast response integrated MEMS microheaters for ultra low power gas detection",[8]

Semiconducting metal oxide (SMO) gas sensors typically operate at a few hundred degrees Celsius and consume hundreds of milliwatts of power, limiting their application in battery-powered devices. An analytical model is presented for the optimization of the heater dimensions, which suggests the minimal power consumption is achieved when heat loss through air conduction and supporting beam conduction are equal. We demonstrate micromachined SMO sensors with optimized microheaters, which consume only ~2 mW of power when operated continuously at 300 ˚C. We also measure an ultra-fast thermal response time of 33 µs via a transient temperature-resistivity response method. The short response time allows the heaters to be operated in ultra-short pulsing mode decreasing the average power consumption to the µW level. These micromachined SMO sensors are used in proof-of-principle experiments as ultralow power hydrogen sulfide SMO gas sensors.

2.9 "A Modular 1 mm^3 Die-Stacked Sensing Platform With Low Power I^{2}C Inter-Die Communication and Multi-Modal Energy Harvesting",[9]

A1.0mm^{3}general-purpose sensor node platform with heterogeneous multi-layer structure is proposed. The sensor platform benefits from modularity by allowing the addition/removal of IC layers. A new low power I^{2}C interface is introduced for energy efficient inter-layer communication with compatibility to commercial I^{2}C protocols. A self-adapting power management unit is proposed for efficient battery voltage down conversion for wide range of battery voltages and load current. The power management unit also adapts itself by monitoring energy harvesting conditions and harvesting sources and is capable of harvesting from solar, thermal and microbial fuel cells. An optical wakeup receiver is proposed for sensor node programming and synchronization with 228 pW standby power. The system also includes two processors, timer, temperature sensor, and low-power imager. Standby power of the system is 11 nW.

2.10 "From Radio Telemetry to Ultra-Low-Power Sensor Networks: Tracking Bats in the Wild",[10]

Sensor networks have successfully been used for wildlife monitoring and tracking of different species. When it comes to small animals such as smaller birds, mammals, or even insects, the current approach is to use extremely lightweight RF tags located using radio telemetry. A new quantum leap in technology is needed to overcome this limitation and enable new ways to observe larger numbers of small animals. In an interdisciplinary team, we are working on the different aspects of such a new technology. In particular, we report on our findings on a sensor-network-based tracking solution for bats. Our system is based on integrated localization and wireless communication protocols for ultra-lowpower systems. This requires coding techniques for improved reliability as well as ranging solutions for tracking hunting bats. We address the technological and methodical problems related to system design, software support, and protocol design. First field experiments have been conducted that showcase the capabilities of our system.

III METHOD AND ANALYSIS

In this paper, we reviewed solar and wind power harvesting, highlighted the utility of using these sources as a pair of complementary power sources, and presented several hybrid harvester architectures based on opensource designs that combine solar/wind harvesting. Our analysis confirms that hybrid harvesters for solar/wind power sources allow embedded systems to be deployed with much less downtime, as compared to systems using solar or wind power alone. We provide four different classes of energy harvester system designs to cover a wide range of trade-offs between cost, complexity, fault-tolerance, and expandability.

IV CONCLUSION

This configuration has a cost advantage and lends itself well to expansion; however, it suffers from reduced fault tolerance, because the single UR-SolarCap board used in this configuration creates a single point of failure for all of the harvested power sources. To test our designs, we conduct experiments on selected configurations of each architecture and evaluate their functionality. Our experimental results confirm the efficacy and versatility of our proposed system architectures and also highlight the advantages and disadvantages of each design. In future work, we plan to introduce versions of our designs that are capable of harvesting a variety of other power sources, in addition to solar and wind.

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