POSITION PAPER: SELF-SUSTAINABLE CYBER PHYSICAL SPACES THROUGH DISTRIBUTED MICRO-SCALE ENERGY HARVESTING

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Cyber physical spaces are composed of various embedded devices vastly distributed, yet tightly connected in the space. The embedded devices include the sensing devices, the processing (and computing) devices, and actuating devices. Due to their tight integration with physical world, many of such devices are under stringent location constraints with no or very limited access to power grid; hence, they are battery operated and wirelessly connected. Long lifetime and ease of deployment of embedded devices in cyber physical spaces are very crucial in order to operate cyber physical spaces in unattended and perpetual fashion. *In this position paper, we focus on enabling "energy" sustainability of such networked embedded devices (and tightly connected to physical world) in cyber physical spaces.* The smart spaces are not sustainable and cannot guarantee continuous operation if the corresponding embedded devices in the space cannot constantly monitor the environmental changes and activities in the space, and collect (and process) the information to actuate the corresponding devices.

Energy harvesting from environment is a promising technology toward achieving energy sustainability in cyber physical spaces. Environmental energy sources are ubiquitous in our surroundings such as light, vibration, heat, radio frequency, and wind. Smart spaces are mostly equipped with ultra-low power sensors and with low data rate and low duty cycle data processing and hence, can significantly benefit from such *micro-scale energy harvesting* [1][2][3]. There can be different manifestations of sustainability in cyber physical systems depending on the availability of energy and application demands. For example, if there is no energy available from renewable sources, energy-sustainability boils down to *adapting* the energy required through various techniques applied at device, network and/or application layers. In case of failure to reduce the energy requirement sufficiently, operations may need to be run from the grid or battery temporarily until the system is back in self-sustainable mode.

<u>Challenges in Micro-scale Energy Harvesting:</u> Several challenges must be tackled to realize the vision of micro-scale harvesting in pervasive spaces:

a) <u>The spatial and temporal variations in scavenging energy from environment leads to uncertainty in energy availability during operation [2][3].</u> The variation in harvesting may depend on environmental variations and/or events occurring in the space.
b) <u>Energy storage and energy efficiency are key challenges in CPS with energy harvesting devices.</u> Energy buffer and/or storage is unavoidable due to spatial and temporal variation in energy harvesting. However, the existing individual energy storage units (stand-alone) cannot provide a sustainable energy solution. Hence, hybrid storage is a promising solution while it requires more sophisticated energy storage management [4].
c) <u>Varying demand of applications manifests itself in application quality requirement and urgency of response (and/or criticality) of the application.</u> In smart spaces, unsupervised events and environmental changes trigger various applications to run in the system. While aiming for the highest application quality and fastest response can resolve the issue but comes with redundant energy and complexity in implementation and it is not feasible in practice.
d) <u>Scavenging energy from various environmental sources is an unavoidable scheme due to uncertainty in energy availability from each source.</u> However, sophisticated controller and harvesting circuitry are required to switch between various sources to power the load and/or store the energy in the storage system [1].

e) Micro-scale energy harvesting is enabled in a vastly distributed scheme. Hence, the scalability in efficient capturing environmental behavior of non-computing components of cyber physical space (i.e., environment-dependent renewable energy sources) through simulations, profiling and/or measurements is a key challenge.

In our previous work, we have developed a middleware framework for wireless sensor networks being deployed in smart spaces [5][6]. This project has focused on data collection applications of WSN in cyberspaces in which harvesting capable sensors collect information about their surrounding environments, update the information at a server via a base station through single-hop or multi-hop adhoc networks and respond to frequent or sporadic monitoring requests (queries) from users. To address these dual issues of scalability and uncertainty, we exploit a key observation that accuracy/fidelity requirements of end applications vary significantly – applications are able to tolerate loss in data quality without significant impact. Our key idea is to take advantage of the data quality-energy tradeoffs and to adapt data quality given energy harvesting constraints to deal with potentially unstable energy sources.

Since harvesting-enabled cyber physical spaces rely highly either on the availability of the environmental energy sources or activity-driven energy sources, the space needs to be evaluated for identifying potential locations for energy harvesting to power CPS devices. Equally important but much less studied are deployment issues related to energy harvesting at micro-scale and its integration with deployment phase. Of particular interest in this position paper is the site survey of the space to capture the spatial and temporal variations of energy harvesting. As opposed to large-scale harvesting in which energy scavenging occurs in a centralized location, potential locations for micro-scale harvesting are distributed all over the space. There is a need for a holistic, yet systematic, solution to reduce the complexity of site survey of the space to capture energy harvesting behavior of the space in energy harvesting with minimum or no intervention with the infrastructure and existing embedded devices in the space. Existing works in energy harvesting-aware cyber physical systems and wireless sensor networks lack in systematic guidance on energy availability in the space. They mostly reply on historic or statistical data to estimate the energy profiles. However, the dynamics and uncertainty in availability of such energy sources demands a real time update of energy status of the space. Hence, we propose to design and to evaluate techniques to capture harvesting behaviors of cyber physical spaces through the notion of a " ***harvesting map*****".** We propose a *middleware* approach to generate such energy maps.

Micro-scale Energy Harvesting Map of Cyber Physical Spaces: We propose to develop a framework called HarNESS (Harvesting-aware Networked Embedded Systems in Smart Spaces) that supports a range of self-sustaining smart space applications through the use of energy harvesting. Our framework consists of networks of HarNESS devices connected to each other and to a collection platform/server through wireless network. Each HarNESS device is equipped with single or multiple types of sensing/actuating, data storage, computing, energy storage, communication circuits, and/or harvesting circuits. HarNESS is envisioned/implemented as a middleware framework which brings harvesting awareness in various aspects controlled by middleware in embedded devices in cyber physical spaces. HarNESS utilizes external input sources such as environmental conditions (e.g., solar maps or wind maps provided by NREL), activity plans and smart space usage schedules for both the initial deployment of devices and periodic (daily, hourly) planning of activities. Energy harvesting statistics during harvesting are collected from various sources such as onboard harvesting measurement circuit embedded in the space or the energy storage status of the devices. Such information is aggregated into short and long term harvesting behavior for use by the other HarNESS modules. We will explore a family of policies for adaptation to current energy and harvesting availability both at the server and at HarNESS devices (client). For example, the actual harvested energy rate could be lower than the predicted average rate. In the extreme case, a node may exhaust its harvested energy; and may currently not in a position to harvest quickly enough to meet the dynamic sensing demands. To address these situations, we will develop dynamic actuation techniques where HarNESS nodes can trigger one or more of the following: a) Actuate backup battery sources on board (not preferred); b)Dynamically actuate controllable harvesting sources (e.g. turn on light, suggest user or client to move to another nearby location); c)Dynamically actuate alternate on-board sensors that have lower energy demands and capture event with lower quality levels (e.g. use onboard motion sensor instead of video capture); and d)Trigger actuation of nearby HarNESS devices with adequate capacity (in a localized manner) to sense the phenomena of interest (turn on devices in a nearby HarNESS node that is currently not activated).

Our objective is to generate a harvesting map of cyber physical spaces with HarNESS framework. We propose to decompose the space into a set of regions such that in each region, we define the level of potential energy harvesting for a given period of time (current or near future). In order to provide a systematic and scalable energy harvesting map of cyber physical spaces, we outline the three challenges as follow:

1. *Granularity of Energy Map:* The finer granularity, the more details are provided to the user devices in the space. However, it comes with high computational cost. On the other hand, at micro-scale energy harvesting, there are several parameters that can affect the energy harvesting rate at different locations. For example, for solar energy, the shading, tilt, and altitude affect the amount of energy being harvested. Such parameters can drastically change from one location to another location in the space. We need to provide scalable approaches to measure the effect of such parameters in estimating the energy harvesting profile for each region in the map.
2. *Efficient and Accurate Energy Map Update*: Given that the energy availability changes over time, we need to provide an efficient, and yet acceptably accurate update of the map periodically or driven by events in the space. In order to receive update on the energy status, the energy status on Harness nodes (clients) and the global energy estimation profile are guiding the map when and how much to update.
3. *Hybrid Energy Harvesting Map:* The map should support hybrid and multi-layer energy harvesting map. Given that harvesting from various sources is becoming an unavoidable scheme for energy sustainability, the energy map needs to demonstrate energy harvesting levels from various sources in each region. Given that the characteristics of each source can be very different, unifying the energy harvesting profile from various sources in a single map can be challenging. Hence, multi-layer maps or maps with multiple levels of abstraction or granularity could be a possible solution.

In summary, large scale cyber physical spaces as described and envisioned in this position paper are inevitable given the increasing ability to sense, observe and manipulate activities in physical spaces. The key deployment challenge in such spaces is continuous and sustained operation. Self-operating and self-sustaining infrastructures, facilitated by combining harvesting technologies with observation capabilities can have a significant impact in how such infrastructures are deployed and operated. The proposed research plans, once accomplished will enable ubiquitous integration of wireless sensing capabilities into cyber physical spaces and pave the way toward *green* and *sustainable* cyber physical infrastructures of the future.

References

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