Ph.D. in Information Technology
Thesis Defense

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Sala Seminari Nicola Schiavoni and online by Zoom

Andrea MAIOLI – XXXV Cycle

Breaking programming abstractions boundaries to increase the efficiency of intermittently-powered computers

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Abstract:

Battery-less devices represent a great opportunity to enable a sustainable Internet of Things: ambient energy harvesting replaces batteries, leading to zero-maintenance systems with a low environmental impact. However, despite potentially supplying unlimited free energy, ambient energy is irregular, unpredictable, and usually insufficient to power battery-less devices continuously. Therefore, battery-less devices experience frequent and unpredictable energy failures that lead to intermittent computation, as devices compute only when sufficient energy is available.

The presence of energy failures introduces several connected challenges. Unlike mainstream platforms, battery-less devices consist of highly constrained microcontroller units that run single non-concurrent programs and lack an operating system to manage energy failures. Therefore, when battery-less devices shut down due to energy failures, they lose the computational state and, in the next power cycle, they restart the computation all over again. To ensure battery-less devices progress in their programs, they periodically need to save their program state onto a non-volatile memory location, which is persistent across energy failures, to restore it when the energy returns. Although this ensures program forward progress across energy failures, battery-less devices may experience unexpected behaviors, producing results that differ from those of an equivalent continuous execution.

Ensuring program forward progress and avoiding unexpected behaviors introduce energy and computation overhead detrimental to battery-less devices' performance. Therefore, efficient energy management becomes essential to extract the most possible work from harvested energy, as it supplies an unpredictable, limited, and scarce amount of energy.

The PhD research described in this thesis tackles these challenges and provides several contributions to the state of the art.

We first work on the first multi-year deployment of battery-less devices that monitor the structural conditions of an archeological site. We devise three system design iterations, where we initially deploy battery-powered systems. Due to the high maintenance efforts of frequent battery replacements, we eventually switched to battery-less systems powered with kinetic and thermal energy. Our final design achieves zero-maintenance battery-less operations without compromising end-user requirements, as its sensed data provides comparable insights to battery-powered systems.

We then target intermittence anomalies, consisting of unexpected behaviors caused by energy failures. We classify intermittence anomalies and identify new types of anomalies previously overlooked by existing literature, which may happen whenever devices interact with the environment. We devise a set of techniques to analyze their occurrence, and we design ScEpTIC, an open-source tool to test intermittent programs.

Building on our work on intermittence anomalies, we devise intermittence awareness, a program design pattern that intentionally allows the occurrence of specific intermittence anomalies to gain new information regarding intermittent executions of programs. We show the potential of intermittence awareness by designing an intermittence-aware technique that reduces the energy overhead required to preserve the computation achieved inside loops. On average, our technique demonstrates a 35.2x lower energy consumption and a 48.4x faster workload completion time.

Next, we focus on improving the energy efficiency of mixed-volatile platforms, which feature a directly-addressable non-volatile memory location where developers can manually allocate portions of the program state. We design ALFRED, a virtual memory abstraction and compilation pipeline for mixed-volatile platforms that automatically identifies the most efficient mapping of the program state across volatile and non-volatile memory. Our experiments show that ALFRED reduces programs' energy consumption by up to two orders of magnitude.

Finally, we focus on ensuring that battery-less devices always operate in the most efficient settings. We devise a system design to efficiently regulate supply voltage and clock frequency in highly resource-constrained battery-less devices. We then implement two hardware/software co-designs that capture these features. Our designs reduce battery-less devices' energy consumption by up to 170% and workload completion time by up to one order of magnitude.

PhD Committee

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