Delft University of Technology
Master's Thesis in Embedded Systems

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Master's Thesis in Embedded Systems

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Abstract

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Preface

TODO MOTIVATION FOR RESEARCH TOPIC

TODO ACKNOWLEDGEMENTS

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Chapter 1

Introduction

1.1 Motivation

The Internet-of-Things (IoT) is a promising vision which enables billions or trillions of sensor devices to be connected [12]. A common bottleneck for such devices is the energy supply. Batteries are large, expensive, heavy and wear out after several years.

A sustainable solution is energy harvesting where a device collects it's energy from the environment for instance solar, radio frequency (RF), thermal or kinetic energy.

However, developing software for such devices comes with a challenge. Environmental energy can be scarce, causing frequent power failures [5]. This contrasts with the standard assumption that programs run continuously throughout execution. The programmer has to take care of this intermittent behavior by for instance storing data to non-volatile memory at certain intervals. The available energy tends to be random, making it difficult to predict how long a program can execute before the next power failure.

It is hard to conduct repeatable tests due to the random nature of the energy source. While comparing two algorithms, it is impossible to conclude that one algorithm outperforms the other without knowing how much the difference in available energy contributed to the result.

1.2 Research goal and contributions

Provide a remote accessible testbed to accelerate the development in applications for batteryless devices for those who do not have the resources or tools them selfs and assist developers in finding bugs caused by intermittent behavior.

The proposed architecture of the testbed is shown in Figure 1.1

Flicker [12] would be an ideal platform to use as device under test (DUT), because it supports many software configurable peripherals and has the MSP430 as its core, a common micro controller in low-power applications. An WISP [18] could be a possible DUT.

Ekho [11] would complement this setup because it can emulate various energy harvesting conditions. An alternative to Ekho would be toggling the power source by a configurable frequency and duty-cycle. Besides emulating, real energy harvesting sources can be used. A configurable light source can be used to power solar panels. An RFID reader can be used to harvest RF energy.

Several methods can be used to track the progress and outcome of a test: serial console (printf), GPIO tracing (logic analyzer), memory dumping and a debugger (possibly energy aware [7]).

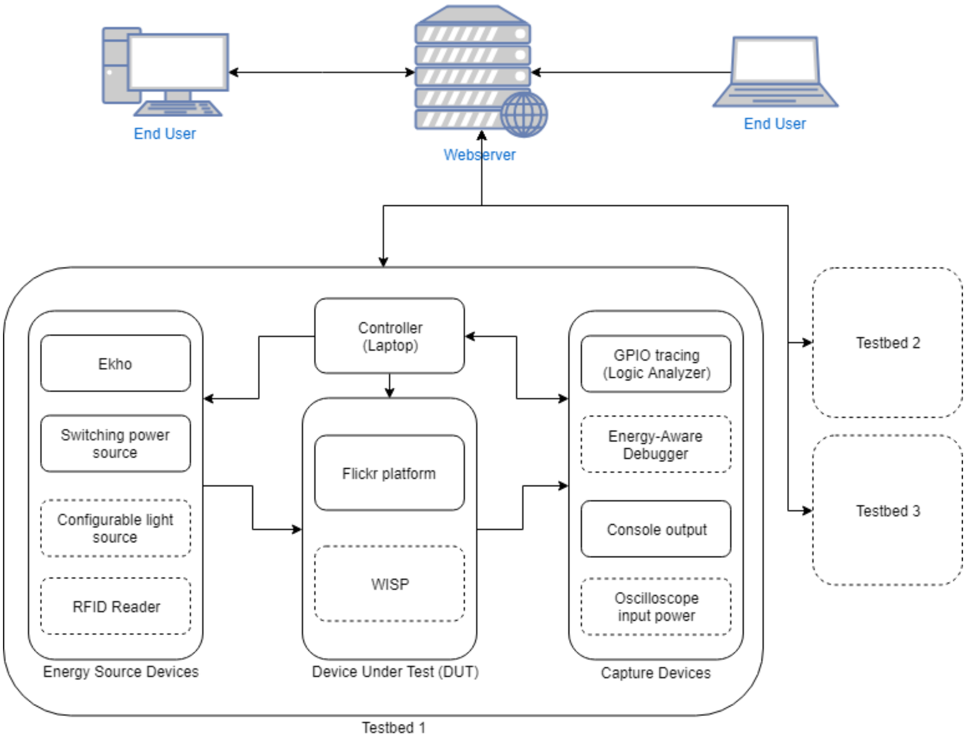

Figure 1.1: Proposed testbed architecture. The dotted lines show optional modules.

1.3 Thesis outline

TODO ORGANISATIONAL DESCRIPTION OF THESIS

Chapter 2

Related Work

The field of energy harvesting devices is promising, but still immature and only a few companies provide such devices commercially. We give an overview of several energy harvesting platforms, both research related and commercial.

Writing software for intermittent devices comes with the challenge of handling frequent and random power cycles. We will discuss which programming models have been developed to counter this issue.

For batteryless, intermittently powered devices there are no publicly available testbeds. Work of [1] enlists properties and features that such a testbed should have, as well as presenting a minimal implementation. The authors call for a more coordinated action in this domain research.

On the other hand there are dozens of existing testbeds for battery-based wireless sensor networks (WSN). There have been many survey published in the past years that compare each of them in detail (see for instance [**?**], [**?**]). Our goal here is to revise these comparative studies expanding it with the recent developments in testbed deployments.

Besides these testbeds, we will discuss several tools which help in developing applications for batteryless devices.

2.1 Energy Harvesting Platforms

In this section a brief overview is given of batteryless energy harvesting platforms using various energy sources. This has been surveyed in [21], [19] ,[22] and [14]. Energy harvesting and it's potential with respect to WSNs has been surveyed in [3] and [6].

Table 2.1 shows some popular and recent developed platforms in scientific research. In Table 2.2 show several companies which are commercially active in the field of energy harvesting devices.

Platform	Description	MCU	Radio	Energy Harvester	Energy Source	Year	Citations
WISP [18]	Family of sensors that are powered and read by UHF RFID readers	MSP430	Backscattering	Transducer and rectifiers	RF	2008	639
Flexible AD PZT Energy Harvester [13]	Self-Powered Wireless Sensor Node Enabled by an Aerosol-Deposited PZT Flexible Energy Harvester	MSP430	CS2500	Flexible piezoelectric energy harvester	Kinetic	2016	65
Umich Moo [24]	Improvement on design of WISP	MSP430	Backscattering	Transducer and rectifiers	RF	2011	63
Monjolo [9]	Energy-Harvesting AC Power metering which draws zero power under zero load conditions	MSP430	CC2420	CR2550, LTC3588	Power line energy harvesting (magnetic field)	2013	45
SPWTS [20]	A novel self-powered wireless temperature sensor based on thermoelectric generators	nRF24LE1	Build in MCU	TEC12706	Thermal	2014	31
Flicker [12]	Configurable development board for batteryless IoT	MSP430	CC1101, nRF51822, backscattering	Solar cell, transducer and rectifiers, LTC3588,	Solar, RF, Kinetic	2017	11
Capybara [8]	Co-designed hardware/software power system with dynamically reconfigurable energy storage capacity	MSP430, CC2650	CC2650	TrisolX solar panels, low-power voltage source	Solar, energy source emulation	2018	11
Pible [10]	BLE batterlyless platform	CC2650	Build in MCU	Solar panels	Solar	2018	2

Table 2.1: Research Based Energy Harvesting Platforms.

Company	**Description**	**MCU**	**Radio**	**Energy Harvester**	**Energy Source**
EnOcean	Various batteryless solutions for i.e.Building Automation and Smart Home	8051 processor	TCM 3x0	ECO 200, ECS 300, ECT 310 Perpetuum	Solar, motion, thermal
Powercast	Provides wireless power solutions, RFID tags, RF power transmitter, RF power harvester	PIC24F	IEEE 802.15.4 transceiver, TX91502	PCC110	RF
Williot	Makes a batteryless bluetooth beacon device based on RF harvesting	ARM processor	N/A	N/A	RF
PsiKick	Provides batteryless monitoring solutions to mainly the industry. Related to the university of Virginia and Michigan.	Custom ULP SoC, ARM architecture [23]	Build in SoC	N/A	Solar, thermal
Bellutech	BelluTechs patented batteryless wireless miniature sensors continuously track and record exposure to environmental and operating conditions.	N/A	N/A	N/A	RF
Matrix Industries	Makes a batteryless thermoelectric powered smartwatch	N/A	N/A	N/A	Thermal

Table 2.2: Commercial Energy Harvesting Platforms.

2.2 Programming Models For Intermittent Computing

To handle the intermittent behavior of energy harvesting devices, several programming models have been developed. These can be divided into three main categories: out-of-place checkpointing, in-place checkpointing and non-volatile processors shown in Figure 2.1.

2.2.1 Out-of-place Checkpointing

Devices using this model save or *checkpoint* the state of the system in external storage. Simply storing the whole state into non-volatile memory (NVM) is not optimal since it requires energy and only changes comparing to the old checkpoint need to be stored.

The programming models can be divided into two sub categories: *proactive* and *reactive* checkpointing systems.

Proactive systems: These systems actively checks the voltage level of the energy buffer. When it drops below a certain threshold it can checkpoint the system state. MementOS [17] was one of the first programming models for intermittent computing. It supports three strategies on when to check the energy buffer: at the end of every loop, at the end of every function or at fixed time intervals.

A downside of this model is that it can lead to data inconsistency. There is always some execution which is not part of any checkpoint. If that execution involves writing to non-volatile variables, the data can become inconsistent. DINO [16]

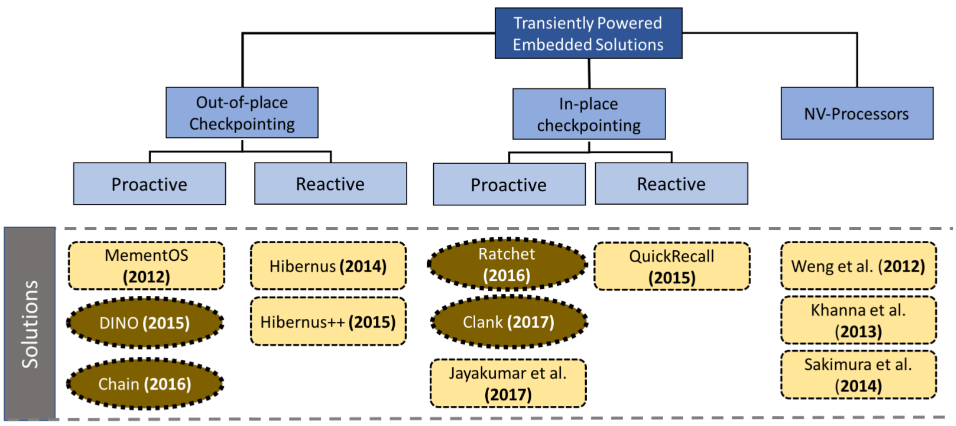

Figure 2.1: Taxonomy of several programming models for intermittent computing [5].

2.3 Wireless Sensor Network Testbeds

Paraphrase this section, taken from https://www.iotbench.e

2.3.1 FIT IoT-LAB

FIT IoT-LAB [2] provides a very large scale infrastructure facility suitable for testing small wireless sensor devices and heterogeneous communicating objects.

IoT-LAB features over 2000 wireless sensor nodes spread across six different sites in France. Nodes are either fixed or mobile and can be allocated in various topologies throughout all sites. A variety of wireless sensors are available, with different processor architectures (MSP430, STM32 and Cortex-A8) and different wireless chips (802.15.4 PHY @ 800 MHz or 2.4 GHz). In addition, open nodes can receive custom wireless sensors for inclusion in IoT-LAB testbed.

2.3.2 Flocklab

Flocklab [15] is a wireless sensor network (WSN) testbed, developed and run by the Computer Engineering and Networks Laboratory at the Swiss Federal Institute of Technology Zurich (ETH Zurich) in Switzerland. FlockLab's key features include:

- FlockLab's observer based testbed architecture which provides services for detailed testing of sensor nodes:
- Time accurate pin tracing
- Time accurate pin actuation
- Power measurements
- Serial interface logging and writing
- Voltage control to simulate e.g. battery depletion

2.3.3 Indriya2

Indriya2 [4] is a three-dimensional wireless sensor network deployed across three floors of the School of Computing , at the National University of Singapore (NUS). The Testbed facilitates research in sensor network programming environments, communication protocols, system design, and applications. It provides a public, permanent framework for development and testing of sensor network protocols and applications. Users can interact with the Testbed through an intuitive web-based interface designed based on Harvard's Motelab's interface. Registered users can upload executables, associate those executables with motes to create a job, and schedule the job to be run on Testbed. During the job execution, all messages and other data are logged to a database which is presented to the user upon job completion and then can be used for processing and visualization.

2.4 Development Tools For Batteryless Devices

Make this section more technical, provide a table comparing tools and add introductory paragraph

2.4.1 Ekho

To counter the issue of randomness in a energy harvesting power source, Ekho [11] has been developed. This an emulator capable of accurately recreating harvesting conditions in a lab. It reproduces the I-V characteristics of energy harvesting sources, allowing developers to choose from a library of energy traces recorded with various sources and environmental conditions.

2.4.2 Flicker

Paraphrase this section

Flicker [12] is a platform for quickly prototyping batteryless embedded sensors. Flicker is an extensible, modular, plug and play architecture that supports RFID, solar, and kinetic energy harvesting; passive and active wireless communication; and a wide range of sensors through common peripheral and harvester interconnects. Flicker supports recent advances in failure-tolerant timekeeping, testing, and debugging, while providing dynamic federated energy storage where peripheral priorities and user tasks can be adjusted without hardware changes.

2.4.3 Energy Aware Debugger

Paraphrase this section

The Energy-Interference-Free Debugger (EDB) [7], is a tool for monitoring and debugging of intermittent systems without adversely affecting their energy state. EDB recreates a familiar debugging environment for intermittent software and augments it with debugging primitives for effective diagnosis of intermittence bugs.

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