Such Title, much education

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Faculty of Science, Technology and Media
Department of Electronics Design
Thesis for the Degree of Doctor of Technology
Mid Sweden University, SE-851 70 Sundsvall, Sweden

Sundsvall **2020**

Akademisk avhandling som med tillstånd av Mittuniversitetet i Sundsvall framläggs till offentlig för avläggande av doktorexamen i electronik den **28 maj 2021 kl. 09:30 i sal cs01, Mittuniversitetet Sundsvall.** Seminariet kommer att hållas på engelska.

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Printed by Mid Sweden University, Sundsvall 2020
ISBN 123456
ISSN 1652-893X

Faculty of Science, Technology and Media
Mid Sweden University, SE-851 70 Sundsvall
Phone: +46 (0)10 142 80 00
Mid Sweden University Doctoral Thesis 231

Abstract

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MPPT Maximum Power Point Tracking

PZT Piezoelectric

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Introduction

Some abbreviations:

1. Piezoelectric (PZT)
2. Maximum Power Point Tracking (MPPT)

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Table 1.1: Piezoelectric Stack

Parameter	Value
C_p	$3.5\,\mu\mathrm{F} \pm 15\%$
d_{33}^{eff}	$230\,\mathrm{nCN}^{-1}$
$\mathrm{tg}\delta$	0.02

1.1 Motivation

[2]

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1.2 Aim

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1.3 Research questions

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Figure 1.1: Miun Logo

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Papers

PAPER I

Energy-autonomous On-rotor RPM Sensor Using Variable Reluctance Energy Harvesting

Energy-autonomous On-rotor RPM Sensor Using Variable Reluctance Energy Harvesting

Conference Paper · June 2019

DOI: 10.1109/IWASI.2019.8791251

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Energy-autonomous On-rotor RPM Sensor Using Variable Reluctance Energy Harvesting

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***Abstract*—Energy-autonomous wireless sensor systems have the potential to enable condition monitoring without the need for a wired electrical infrastructure or capacity-limited batteries. In this paper, a robust and low-cost energy-autonomous wireless rotational speed sensor is presented, which harvests energy from the rotary motion of its host using the variable reluctance principle. A microelectromechanical system (MEMS) gyroscope is utilized for angular velocity measurements, and a Bluetooth Low Energy System-on-Chip (SoC) transmits the acquired samples wirelessly. An analysis on the individual subsystems is performed, investigating the output of the energy transducer, the required energy by the load, and energy losses in the whole system. The results of simulations and experimental measurements on a prototype implementation show that the system achieves energy-autonomous operation with sample rates between 1 to 50 Hz already at 10 to 40 rotations per minute. Detailed investigations of the system modules identify the power management having the largest potential for further improvements.**

***Index Terms*—Energy harvesting, variable reluctance, energy-autonomous sensors, inertial RPM measurement**

I. Introduction

With advancements in sensing, processing and communication technologies, industrial condition monitoring gains in popularity, enabling smart industrial machines and components [1]. Rotating parts are omnipresent in industrial applications, making their monitoring an essential task. Enabled by wireless communication technologies, sensing can be performed directly on the rotating object, providing data on, for example, rotational speed [2], [3].

Due to the fundamental difficulty of a wired power supply on rotating parts and the capacity and lifetime limitations of batteries, energy harvesting poses a competitive approach for supplying on-rotor electronic systems with the energy they require. Despite the growing research volume in energy harvesting [4], [5], experiences from end-to-end energy harvesting system designs are still limited.

In this paper, we report on the design, implementation and analysis of an energy-autonomous on-rotor RPM sensor system. The system uses a MEMS gyroscope for the measurement of the rotor's angular velocity and reports the acquired data wirelessly. The sensor system is powered by a variable reluctance energy harvester (VREH), exploiting the relative motion between the rotor and a stator based on electromagnetic induction. The system is particularly designed for applications with low rotational speeds of large-diameter shafts, making the utilization of standard electromagnetic generators infeasible. Moreover, the system includes a power management unit, coupling the energy transducer and the load.

With the overall aim to analyze the end-to-end implementation of the on-rotor RPM sensor system, we investigate the performance of each sub-module, as well as the performance of a full prototype implementation. As a result, the key contributions of this paper are: (i) an energy-autonomous RPM sensor design, outperforming previously reported solutions; (ii) an end-to-end energy harvesting system implementation, investigating generated and required energy levels by the energy transducer and load, respectively; and (iii) an analysis of limitations in the system, identifying opportunities for further system optimizations.

Previously reported energy harvesting RPM sensor systems include the works by Parthasarathy et al. [6], and Buccolini and Conti [7]. In [6], the authors utilize a commercial variable reluctance transducer in order to implement an autonomous wheel speed sensor for automotive applications. The wheel speed sensor acts as an energy transducer to the wireless acquisition unit and a theoretical output power of $1\,\mathrm{mW}$ at $300\,\mathrm{rpm}$ is estimated. The authors, however, do not perform a detailed analysis of available power levels in the system, nor report achievable sample rates at different operating conditions. In [7], a self-powered wheel speed sensor for bicycles is proposed, utilizing an electromagnetic transducer based on the relative motion of a coil and magnets. The authors investigate the performance of the transducer, power management, and sensor systems. The measurement of rotational speed, however, is limited in resolution by the event-based implementation, generating pulses only on full rotations. Moreover, the proposed system generates sufficient power levels only at relatively high rotational speeds. In contrast to the previous work, we utilize an inertial rotational speed measurement, aiming at an accurate and energy-autonomous operation already at low rotational speeds, i.e., $10\,\mathrm{rpm}$ to $60\,\mathrm{rpm}$.

II. System Design and Implementation

A system overview of the proposed energy-autonomous, on-rotor RPM sensor is depicted in Fig. 1. The system follows a common architecture for a wireless sensor node, containing

This work was financially supported by the Knowledge Foundation through fund ASIS 20140323 and by VINNOVA through grant 2017-03725.

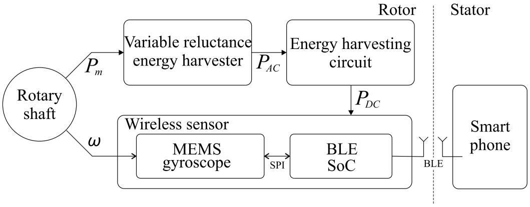


Fig. 1. Overview of the energy-autonomous on-rotor RPM sensor design, where P_{M} is the mechanical power, P_{AC} is the alternating current electrical power, P_{DC} is the direct current electrical power, and ω is the rotating speed of the rotary shaft.

a control/computation unit, a radio transceiver, and a sensing unit. In order to make the sensor system self-powered, moreover, the system includes a kinetic energy transducer that utilizes the rotary motion of the monitored host, as well as an energy harvesting conversion unit that adjusts the transducer's output to the load requirements.

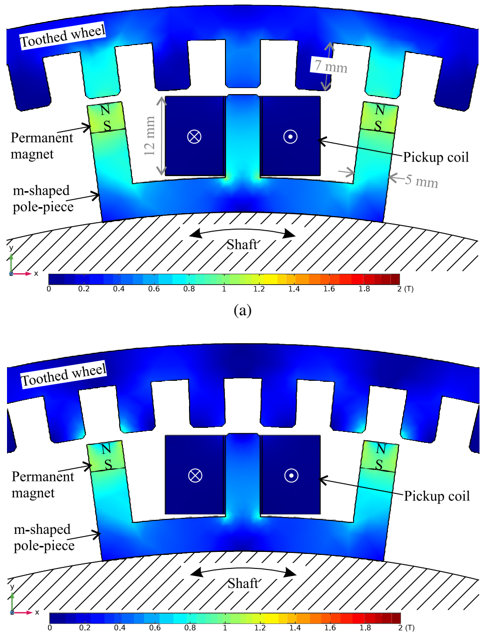
A. Wireless RPM Sensor

The core of the wireless RPM sensor design is a MEMS gyroscope, implementing an inertial approach to the measurement of rotational speed. Due to their integration and mass production, MEMS gyroscopes are highly competitive with respect to cost, size and power consumption. They, moreover, have a number of advantages over traditional event-based solutions (e.g., optical or magnetic encoders), which do not scale well to large shaft-diameters and low rotation rates. A closer investigation of the performance of MEMS gyroscopes can be found in [8], suggesting competitive performances to traditional approaches at much lower costs. In this system, a Bosch BMG-250 has been selected for the implementation, due to its small physical footprint ($2.5\,\mathrm{mm} \times 3.0\,\mathrm{mm}$) and low current draw in operation ($850\,\mu\mathrm{A}$).

The gyroscope is connected to a Rigado BMD-350 SoC, integrating an ARM microcontroller and a Bluetooth Low Energy (BLE) wireless transceiver. The angular velocity values of the axis aligned to the rotation direction are read out in digital format through a high-speed SPI bus. The sensor data is then wirelessly transmitted using the BLE transceiver.

B. Variable Reluctance Energy Harvester

Utilizing inertial forces for the RPM measurement, the wireless sensor is mounted directly on the rotating object. Consequently, electrical energy needs to be provided to all active components on the rotor. The conversion of kinetic energy from the rotating object is a desirable alternative to a capacity-limited solution such as batteries. In the proposed system, an electromagnetic approach based on the variable reluctance principle is used. A variable reluctance energy harvester (VREH) exploits the relative movement between a pickup unit, containing a coil and magnets, and a ferro-magnetic structure that affects the system's reluctance (e.g., a toothed wheel).



(a)

(b)

Fig. 2. Magnetic flux density distribution of the VREH topology at the two extreme positions, (a) aligned position and (b) unaligned position.

Figure 2 illustrates the on-rotor VREH structure applied in this work, demonstrating the magnetic flux distribution in its two extreme positions. The utilized pickup unit has an m-shape with two permanent magnets and a center coil, which has previously been demonstrated to outperform other pickup unit structures [9]. The rotation of the shaft results in a periodic arrangement variation between aligned position (Fig. 2a) and unaligned position (Fig. 2b). As a result of the varying reluctance, a magnetic flux change occurs in the core of the coil, inducing an alternating voltage according to Faraday's law.

By connecting an impedance matched load (i.e., $Z_{\mathrm{Coil}} = Z^{*}_{\mathrm{Load}}$) to the pickup coil, maximum power can be transferred to the load. The power level is a function of multiple system parameters and operating conditions and can be estimated according to [9] as

$$P_{\mathrm{L}} = \frac{N_{\mathrm{Coil}}^2}{8R_{\mathrm{Coil}}} \Delta_{\phi}^2 \left[\frac{\omega N_{\mathrm{tooth}}}{2\pi} \right]^2 . \tag{1}$$

Herein P_{L} is the output power at the matched load, N_{Coil} is the number of coil turns, Δ_{ϕ} is the magnetic flux difference between aligned and unaligned positions, ω is the angular velocity, and N_{tooth} refers to the number of teeth in the toothed wheel. Neglecting the inductive part of the coil's impedance, an accurate estimation is only achieved at low operation frequencies.

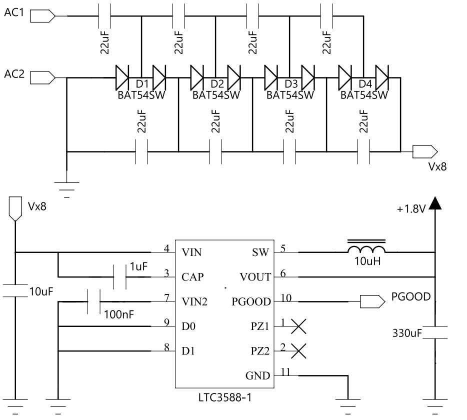


Fig. 3. Schematic overview of the energy harvesting conversion circuit, containing a four-stage Cockroft-Walton voltage multiplier and an LTC3588-1.

C. Electrical Conversion

Due to the AC output of the VREH unit, an electrical conversion module implementing AC-DC conversion is required. The conversion module is designed around a commercial energy harvesting integrated circuit, namely Analog Devices LTC3588-1. This device provides low quiescent consumption and high efficiency at relatively low output currents.

Although the LTC3588-1 allows for direct AC inputs through an internal bridge rectifier, an external rectification based on a four-stage Cockroft-Walton voltage multiplier [10] is implemented. This is motivated based on the relatively low voltages generated by the VREH transducer, as well as the high voltage drop over the bridge rectifier. The four-stage voltage multiplier rectifies the AC voltage and results in a DC voltage with an 8-fold multiplication. It thus enables operation even at low angular velocities, lifting the VREH output voltage to a range compatible with the LTC3588-1 input requirements (i.e., $2.7\,\mathrm{V}$ to $20\,\mathrm{V}$). While a pickup coil with a larger number of turns could be used as an alternative, this approach would result in a significantly larger space occupation and an increased coil resistance.

A schematic view of the power management module design is shown in Fig. 3. The output of this module is a stable $1.8\,\mathrm{V}$ DC supply to the wireless sensor.

III. Experimental Setup

The wireless sensor is specifically designed for the purpose of monitoring angular velocity in low-speed and large-shaft rotating machines. Examples of such applications include feeders and drums in the cement industry, drives in food and mining industries, mixers and roll mills in the rubber and plastic industries, as well as heavy machines such as cranes, excavators, and wind turbines [8], [11].

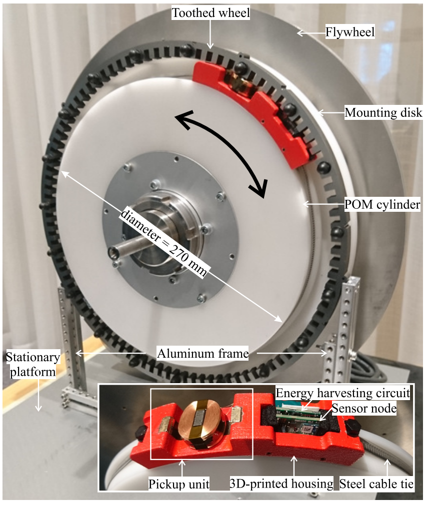


Fig. 4. Experimental setup generating the conditions of a low-speed, large-shaft rotating machine. A close-up of the mounted sensor system is provided in the inset.

In this paper, the specific requirements of large-scale hydraulic motors for industrial applications are used to investigate the system performance. As a result, a shaft diameter of $270\,\mathrm{mm}$ has been chosen, and evaluations are conducted under low rotational speed in the range of $10\,\mathrm{rpm}$ to $60\,\mathrm{rpm}$.

Figure 4 depicts the experimental setup, containing a polyoxymethylene (POM) cylinder that emulates the system's rotating shaft. The POM cylinder is driven by a controllable DC motor, operating at low rotational speeds. A toothed wheel made of electric steel is mounted on a stationary mounting disk. The on-rotor unit integrates the wireless sensor node, the energy harvesting conversion circuit, and the VREH pickup unit, being enclosed in a 3D-printed housing and fixed on the rotor surface. The setup creates a mechanical air gap of $1\,\mathrm{mm}$ between the pickup unit and toothed wheel. Moreover, a flywheel is mounted onto the POM cylinder in order to maintain a stable rotation speed and smooth speed transitions.

The pole-piece and toothed wheel are laminated structures stacked by 28-layers of electrical steel NSC-35H230, resulting in a stack depth of $10.15\,\mathrm{mm}$. Two N50-NdFeB permanent magnets provide the constant MMF in the pickup unit, and are glued on the pole-piece. The pickup coil is wound on the center pole of the pole-piece, and its two terminals are connected to the conversion circuit board (*AC1* and *AC2*, as shown in Fig. 3).

For simplicity, we configure the BLE SoC to operate in a beacon mode to transmit the payload in advertisement packages. Consequently, this configuration requires no scan response from the smartphone. The transmission power of the BLE transceiver is set to $-20\,\mathrm{dBm}$, resulting in a low power consumption while transmitting to a nearby operator.

TABLE I
DURATION AND ENERGY CONSUMPTION OF WIRELESS SENSOR STATES

State	Description	Time (ms)	Energy (μJ)	Contribution (%)
SPI-wu	Sensor wakeup	0.24	1.33	1.6
S-init	Sensor initialization	32.48	25.89	31.3
S-meas	Sensor measurement	27.32	37.78	45.6
SPI-tx	Sensor readout	0.25	1.53	1.8
BLE	BLE transmission	3.73	16.26	19.7
Total		64	82.79	

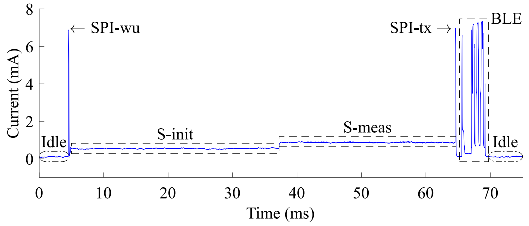


Fig. 5. Current profile for the acquisition of one sample on the wireless sensor. The total duration of a sample acquisition is 64 ms.

The transmitted payload is the sensor data, consisting of two 16-bit readings (i.e., one for angular velocity, and one for temperature).

IV. SYSTEM EVALUATION

The evaluation of the system is conducted in two steps. Firstly, the performance of each module is evaluated individually in order to provide a better understanding of available energy, required energy, and losses in the system. Secondly, the system is integrated into a full system prototype, providing measures of the overall system performance.

A. Wireless Sensor Energy Consumption

The energy consumption of the wireless sensor defines the required energy to be generated for correct system operation. Operating at a constant supply voltage of $1.8\,\mathrm{V}$, the energy consumption can be deducted from current measurements. The current profile of the wireless sensor has been acquired, measuring the voltage drop over a $1.068\,\Omega$ low-side shunt resistor. The measurements have been performed with a Keysight MSOX3024T oscilloscope in differential mode.

Figure 5 shows the current profile for a sample acquisition of the wireless sensor, annotating key phases in the process. The total sampling period is $64\,\mathrm{ms}$ long, with the highest power demands posed by the BLE SoC. Table I lists the individual phases together with their time and energy requirements. From this table it becomes obvious that it is the gyroscope that dominates the energy footprint (i.e., about $77\,\%$), despite its low power demand. With approximately $83\,\mu\mathrm{J}$, the overall energy footprint of a single sample is low.

In addition, the current draw of the wireless sensor during idle state is approximately $5\,\mu\mathrm{A}$. At low duty cycles, this idle current results in a significant contribution to the overall energy need, whereas its impact reduces dramatically at the higher sampling intervals targeted for this system.

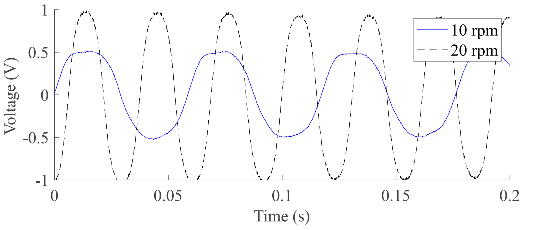


Fig. 6. Output voltage measurement of the pickup coil over an impedance matched load at $10\,\mathrm{rpm}$ and $20\,\mathrm{rpm}$, respectively. Differences in output amplitude and frequency can be observed.

B. VREH Performance

In order to evaluate the performance of the VREH, its output power under different operating conditions can be used as a metric. Under ideal conditions, the attached load is impedance matched to the VREH transducer, maximizing the power transfer between source and load. Due to the relative low frequencies of interest in this study, the impedance matching condition can be simplified to $R_{\text{Coil}} = R_{\text{Load}} = 180.5\,\Omega$.

Figure 6 shows the output voltages of the VREH under two rotating speeds and with matched resistive load. It can be seen that with changing angular velocity, both amplitude and frequency of the output voltage are affected. The ideal output power in these scenarios can be estimated based on the RMS voltage and the load condition, such that

$$P_{\text{out}} = V_{\text{RMS}}^2 / R_{\text{Load}}\,. \tag{2}$$

Already at $10\,\mathrm{rpm}$, for example, the RMS output voltage is $405\,\mathrm{mV}$, resulting in an output power of approximately $910\,\mu\mathrm{W}$. This theoretically enables for a sample rate of $10\,\mathrm{Hz}$.

Figure 7, moreover, depicts how the output power of the VREH scales with increasing rotational speed. The results in this figure are obtained through three-dimensional finite element simulations conducted in COMSOL Multiphysics. The simulation results are experimentally verified in the range of rotation speeds compatible with the experimental setup (see Section III), demonstrating a good match between simulations and experiments. In the observed range, the output power follows a roughly linear dependency with the rate of rotation, leading to almost $15\,\mathrm{mW}$ at $60\,\mathrm{rpm}$. The linear relationship is a consequence of impedance mismatch at higher rotational speeds, neglecting the imaginary part of the impedance. For reference purposes, the theoretical output under true impedance matching is included in the figure.

C. Conversion Efficiency

As previously described in Section II-C, an AC-DC conversion subsystem is required to provide a stable DC voltage to the load. This subsystem inevitably consumes a portion of

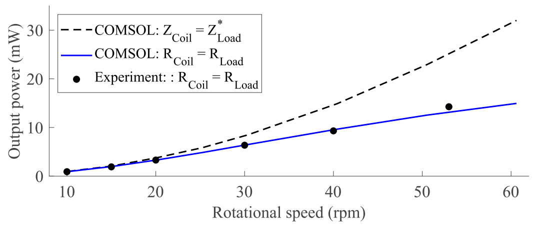


Fig. 7. Average output power of the VREH at different rotational speeds. Comparison between resistive and complex conjugate matching demonstrates little influence below 20 rpm.

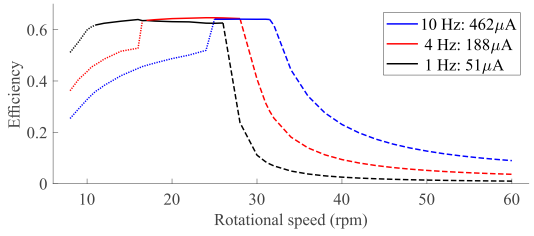


Fig. 8. Power conversion efficiency of the energy harvesting conversion circuit for three sampling frequencies of the wireless sensor at different rotating speeds.

the harvested energy, which can be expressed as its conversion efficiency. The expected efficiency of the commercial energy harvesting IC (LTC3588-1) is well described in the device datasheet. In this design, however, an additional rectification stage has been added, affecting the overall conversion efficiency.

In order to evaluate the overall efficiency of the conversion module, SPICE simulations have been performed containing both the voltage multiplier and the LTC3588-1. The SPICE simulations use a voltage source as input, implementing the specific properties of the VREH transducer. Exemplar results of these simulations are shown in Fig. 8, providing the overall conversion efficiency as a function of the rotational speed for a selection of sample rates (i.e., load currents). It is noteworthy to remember that a change in rotational speed leads to different amplitudes and frequencies of the input AC voltage. In the depicted range the input voltages (peak) range from approx. 1 V to 5 V, with frequencies from approx. 20 Hz to 100 Hz.

Figure 8 shows three distinct phases for each sample rate case. The dotted part at low rotational speeds indicates input conditions insufficient to lead to a stable output voltage of 1.8 V. The second, solid part indicates normal operation, where the overall conversion efficiency is stable at approx. 61.5 %. Finally the dashed part at higher rotational speeds demonstrates the effect of input protection, in which a Zener diode guarantees not to exceed the max. input voltage to the LTC3588-1. The start and end conditions for certain phases can be affected by the implementation of the voltage

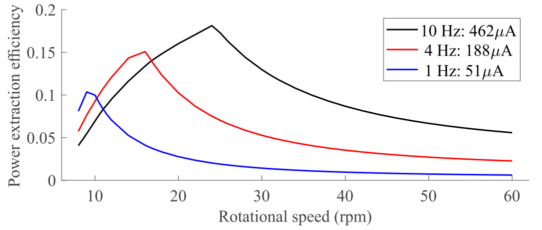


Fig. 9. Power extraction efficiency as a function of rotational speed for different sampling frequencies of the wireless sensor.

multiplier, but a widely applicable solution is difficult to be achieved with this architecture.

D. Full System Evaluation

Finally, the full system performance is evaluated, considering the performance of each subsystem, as well as their interaction. A figure of merit suitable for the system evaluation is the power extraction efficiency (PEE), which describes the ratio of available power to the load with respect to the ideally extractable power from the transducer [12].

Figure 9 shows the estimated PEE of the full system as a function of rotational speed, and for a selection of sampling rates. The results in this figure originate from SPICE simulations of the system implementation. For the PEE, in this regards, two main contributions can be identified. On the one hand, the PEE is affected by the conversion efficiency presented in Section IV-C. On the other hand, connecting the conversion subsystem to the transducer leads to an impedance mismatch, reducing the extracted power as compared to the ideal condition presented in Fig. 7.

The main reason for the impedance mismatch is the large equivalent capacitance of the Cockroft-Walton voltage multiplier. This capacitance could ideally be compensated for by an additional series inductance, but the large values required make an implementation unrealistic. Figure 9, moreover, shows that the PEE is dependent on the rotational speed, providing an optimum operating condition for each load condition.

In order to investigate what effect the available power has on the wireless sensor scenario, the achievable sample intervals are evaluated as a function of the rotational speed. This investigation takes the entire system into account. The results of this analysis are shown in Fig. 10, with the solid curve being a result of the ideal VREH output power, the PEE of the system, and the load requirements presented in Section IV-A. Moreover, this estimation is confirmed by an experimental verification at a set of different rotational speeds.

With increasing output power at increasing rotational speed, the sample interval decreases as a function of rotational speed. However, the sample interval is not only limited by the available power, but also by timing restrictions of the wireless sensor. Consequently, four distinct phases have been indicated in the figure. Phase (a) indicates normal operation according to the sampling sequence as illustrated in Fig. 5. In this operation,

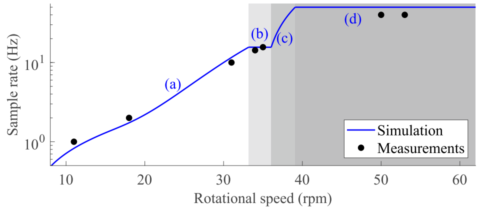


Fig. 10. Estimated sample frequency of the wireless sensor at different rotating speeds

the sample acquisition takes approx. 64 ms. At approx. 33 rpm (start of phase (b)), enough energy is harvested to continuously acquire samples, leading to the maximum sampling frequency of 15.625 Hz in this operating mode.

In order to reach a higher sampling frequency, the operating mode has to be changed. This can be achieved by maintaining the gyroscope in active mode, avoiding its initialization and reducing its readout time. This operating mode will require a higher average power, which is available from approx. 36 rpm and onward. In phase (c), thus, a further reduction of the sample interval with increasing rotational speed can be observed. Finally, phase (d) is reached at approx. 39 rpm. At this point, both gyroscope and BLE transceiver can operate continuously. As a result, the sample interval is limited by the maximum advertisement interval of 20 ms for the BLE communication. Further improvements of sample rates are only possible if switching to a connection-based operation.

Figure 10, moreover, shows that a sample rate higher that 1 Hz is obtained already at approx. 12 rpm. The experimental data shows that this sample rate can be achieved even at slightly lower rotational speeds, at approx. 11 rpm.

V. Conclusion

In this paper, we designed, implemented and analyzed an energy-autonomous, on-rotor sensor system using variable reluctance energy harvesting. The wireless sensor monitors the angular velocity and temperature of a low-speed and large-diameter rotary structure, without the need for a wired power supply or battery. The compact design, including a low-cost MEMS gyroscope and a robust electromagnetic energy harvesting system, is suitable for industrial and cost-sensitive applications.

The results from simulations and a prototype implementation demonstrate that the VREH approach can enable autonomous operation of the wireless sensor already at low rotational speeds. A sample rate of 1 Hz, including sensor initialization, readout, and wireless transmission via BLE, requires approx. 90 µJ. The required power level for this is made available to the load already at 11 rpm.

An investigation of the individual subsystems provides an understanding of the required energy by the wireless sensor; the extractable energy from the VREH transducer under different operating conditions; and the efficiency of the system through conversion losses. Combining the individual modules into a full system prototype, furthermore, demonstrates additional losses due to mismatches in module impedances. As a result, we show that it is the energy harvesting conversion circuit that has a large influence on the power delivery to the load. With power extraction efficiencies below 20 %, a considerable portion of energy that could potentially be harvested by the system is lost. Particularly, impedance matching would help to improve the PEE, but is difficult to be achieved for the utilized conversion circuit implementation, due to the large equivalent capacitance of the voltage multiplier.

For further improvement, thus, an alternative implementation of the electrical conversion is the primary target to be addressed. Besides improving the impedance match between transducer and the conversion circuitry, an AC-DC conversion with high efficiency over a wider operating range would be desirable. In addition, further optimizations on the VREH transducer can be performed, not only improving its output power, but even optimizing for an overall higher PEE.

Nonetheless, we demonstrated that the proposed system design reaches the maximum achievable sample frequency of the underlying technology (i.e., 50 Hz) already at low rotational speeds below 50 rpm.

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PAPER II

On the Modeling of Solar-Powered Wireless Sensor Nodes

On the Modeling of Solar-Powered Wireless Sensor Nodes

Article *in* Journal of Sensor and Actuator Networks · September 2014

DOI: 10.3390/jsan3030207

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J. Sens. Actuator Netw. **2014**, *3*, 207-223; doi:10.3390/jsan3030207

OPEN ACCESS

Journal of Sensor and Actuator Networks

ISSN 2224-2708

www.mdpi.com/journal/jsan

Review

On the Modeling of Solar-Powered Wireless Sensor Nodes

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Received: 4 June 2014; in revised form: 26 June 2014 / Accepted: 14 July 2014 / Published: 4 August 2014

Abstract: Solar energy harvesting allows for wireless sensor networks to be operated over extended periods of time. In order to select an appropriate harvesting architecture and dimension for its components, an effective method for the comparison of system implementations is required. System simulations have the capability to accomplish this in an accurate and efficient manner. In this paper, we evaluate the existing work on solar energy harvesting architectures and common methods for their modeling. An analysis of the existing approaches demonstrates a mismatch between the requirement of the task to be both accurate and efficient and the proposed modeling methods, which are either accurate or efficient. As a result, we propose a data-driven modeling method based on artificial neural networks for further evaluation by the research community. Preliminary results of an initial investigation demonstrate the capability of this method to accurately capture the behavior of a solar energy harvesting architecture, while providing a time-efficient model generation procedure based on system-level data.

Keywords: wireless sensor networks; sensor node lifetime; solar energy harvesting; modeling; simulation; system dimensioning

1. Introduction

Environmental monitoring has been an application domain with a large potential benefit from the utilization of wireless sensor networks since the development of this technology started. As wireless sensor networks do not require a fixed infrastructure, their flexibility of placement enables them to be used at practically any location. Environmental monitoring can thus utilize this technology in order to increase the amount of data being measured in an autonomous manner. As a result, a considerable number of case studies have been presented in the literature, which demonstrate the usage of wireless sensor networks in environmental monitoring applications, e.g., [1–6].

Despite the clear advantages of wireless sensor networks for increased temporal and spatial environmental measurements, a number of system challenges are yet to be overcome in order for wireless sensor networks to become a standard measurement instrument for the environmental sciences. One major challenge (though not limited to environmental monitoring) is the availability of a reliable long-term energy supply. In a similar manner to portable electronic devices, the individual sensor nodes within a wireless sensor network are typically powered by primary or secondary batteries. These energy sources, however, have a limited lifetime and energy storage capacity. Particularly, in application scenarios, which contain a large number of sensor nodes or are deployed in locations that are difficult to be revisited, the additional maintenance demands of manually exchanging or recharging depleted batteries are undesirable.

Energy harvesting—the extraction and conversion of ambient energy—in general and solar energy harvesting, in particular, have gained attraction in the research community in order to reduce the maintenance cost, which is introduced by the limitations of battery technology [7,8]. Utilizing an ambient energy source allows for the state-of-charge of an energy storage element to be continuously replenished. As a result, an optimally-dimensioned energy harvesting system can lead to the perpetual lifetime of the sensor node, which is only limited by the electronic degradation of the system itself, rather than its energy storage capacity.

In comparison to the energy supply from a battery, the dimensioning of a solar energy harvesting system requires a greater number of parameters to be taken into account. These parameters include the harvester architecture with its components to be dimensioned (e.g., the solar panel rating and storage element capacity), the application constraints and its effect on the load (e.g., the sensor node's power consumption in a temporal manner), as well as the deployment location, which determines diurnal and annual cycles that have an effect on the available energy to be harvested. Consequently, the system dimensioning becomes a complex task and can typically not be performed in an easy manner. Nevertheless, the ability to efficiently dimension a solar energy harvesting architecture allows for a size and cost optimization to be performed without increasing the risk for system downtime, which has strong relevance to any wireless sensor system deployed outdoors.

Simulations have been proposed as a solution for the dimensioning problem. Using incoming and outgoing energy levels as the parameters, the behavior of the harvesting system, particularly, with respect to available energy, is simulated in order to evaluate its performance under the specific application constraints. As a result, a number of architectures and/or component choices can be evaluated prior to the deployment of the system. In order for these simulations to provide accurate results, however, the underlying harvesting system has to be modeled in an accurate manner. A number of modeling approaches have been proposed in the literature, but none of them seem to find wider attraction outside the research community.

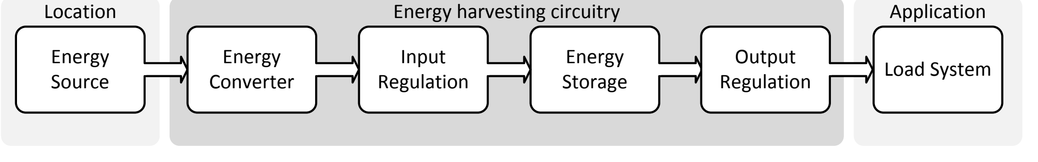
The goal of this paper is to provide a review of the existing modeling approaches for solar-powered wireless sensor networks. We present, classify and analyze the common approaches in order to identify what hinders their adoption. The main focus lies on the utilization of simulations for dimensioning purposes, and each presented modeling approach will be evaluated in this regards. While the modeling of application and location parameters will be briefly addressed, the main focus lies on the modeling of the underlying hardware architectures for solar energy harvesting.

The structure of this paper is organized as follows. Section 2 provides the background on solar energy harvesting architectures and a review of existing implementations, which demonstrates the variety of potential solutions and, thus, the challenge of choosing the most appropriate architecture and its components for a specific application at hand. Section 3 introduces the underlying structure of solar energy harvesting models and reviews methods for the modeling of their individual modules. Based on the challenges of the existing methods that have been identified, Section 4 proposes a data-driven modeling approach as a support method for the architecture selection and dimensioning. Finally, Section 5 concludes the work and presents an outline for further investigations.

2. Solar Energy Harvesting Architectures

An energy harvesting system converts the energy from an ambient energy source to electrical energy in order to supply the connected load. In order for the system to accomplish this task, it typically contains a number of building blocks, which are depicted in Figure 1 in a generalized manner. First and foremost, the system requires a conversion step, which allows for the incoming ambient energy to be converted to electrical energy. Moreover, as most ambient energy sources are intermittent or dynamic in the available energy levels, the energy harvesting systems commonly incorporate one, or several, energy buffers to enable a continuous supply. Finally, in order to perform safe and efficient charging of the energy buffers, as well as to provide acceptable voltage levels to the load, multiple regulation steps are commonly found in any energy harvesting system.

Figure 1. Generalized architecture of an energy harvesting system.



For solar energy harvesting, in particular, the energy conversion takes places through a solar panel, which provides an output current as a function of the solar irradiance and the terminal voltage. As the resulting I-Vcharacteristic is non-linear, the output power level is dependent on the working point of the panel. Maximum power point tracking (MPPT) is thus commonly integrated into the input regulation for large-scale solar energy harvesting systems, while it is argued upon whether it is also suitable for small-scale systems [9,10]. Because solar energy harvesting systems are required to equalize the diurnal and seasonal variations of the incoming solar energy, they typically include energy buffers in the form of batteries and/or capacitors. Furthermore, based on the energy storage technology that has been selected, additional charge management and protection circuits might be required.

The overall aim of the majority of solar energy harvesting systems is to supply a load with power in a continuous manner. Energy-neutral operation is a requirement for the system in order to fulfill this aim. Kansal *et al.* [11] defined energy-neutral operation through the condition:

$$\eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T \rho_{leak}\, dt + B_0 \geq 0 \quad \forall T \in [0, \infty) \qquad (1)$$

where $P_s(t)$ is the supplied power by the energy converter and $P_c(t)$ is the consumed power by the load at time t, respectively. Furthermore, η denotes the charging efficiency, ρ_{leak} the leakage power and B_0 the initial state of charge of the energy storage at time $t = 0$. In essence, energy-neutral operation is achieved if the energy demand of the load can be provided by the energy converter (*i.e.*, the solar panel) or the energy reservoir at any moment in time. The capability of the energy buffer to equalize insufficient ambient energy levels depends on the respective state of charge, which is affected by previous charge and discharge conditions, as well as the continuous losses.

Consequently, a solar energy harvesting system should be dimensioned in such a way that it enables an energy-neutral operation under predefined location and application constraints.

2.1. Solar Energy Harvesting Implementations

Solar energy harvesting has been identified early on as a potential solution to the power supply challenge in wireless sensor networks [12,13]. As a result, a plethora of different architectures and systems have been proposed in the literature [14–21]. This section provides an overview of the existing architectural solutions and implementations, and it illustrates the underlying challenge for the dimensioning task to be performed by the simulation tools. Due to the vast amount of existing systems, a selection has been made that covers the major variations in system architecture, component choice and implementation. For further details, we refer the reader to the respective literature of the individual systems, as well as survey papers, e.g., [22].

A number of wireless sensor network case studies for environmental monitoring utilize off-the-shelf solar energy harvesting systems, which are typically composed of solar panels with ratings of the order of several watts, lead-acid batteries and commercial charge regulators [2,23]. While these solutions work well for applications with a large physical node size and considerable energy demands, they do not scale down in an efficient manner. Consequently, these solutions typically dominate the physical size of the sensor node and require additional resources in order to convert the $12\,\mathrm{V}$ battery voltage to adequate levels for the node's power supply.

This has led to a number of solar energy harvesting systems that directly address the needs of wireless sensor nodes. An overview of these systems, along with their individual implementation choices, is given in Table 1. The greatest variation in these systems can be observed in the implementation of the input regulation and the energy storage, which are, in addition, tightly linked to each other. The typical energy storage technologies include secondary batteries and double-layer capacitors (DLCs). While secondary batteries, commonly lithium- or nickel-based, provide a larger capacity and, thus, can support sensor nodes that have a greater energy consumption, DLCs allow for a greater number of charge cycles to be performed, which ultimately increases the system lifetime in a solar energy harvesting scenario. Moreover, in [15,18], both storage technologies have been combined in a hybrid solution in order to utilize the advantages of each individual technology. In addition to the technology selection itself, the systems vary in the energy storage implementation, which includes the device capacity and the number of cells.

Table 1. Overview of solar energy harvesting system implementations. DLC, double-layer capacitor; MPPT, maximum power point tracking.

System	Solar Panel	Input Reg.	Storage	Output Reg.
Heliomote [14]	400 mW	–	NiMH	DC-DC Boost
Prometheus [15]	200 mW	Pulse Charging (Mote Software)	2x DLC (22 F) Li ion (200 mA h)	–
Everlast [16]	450 mW	MPPT (Mote Software)	DLC (100 F)	DC-DC Boost
Alippi *et al.* [17]	400 mW	MPPT (Dedicated Software)	NiMH (300 mA h)	–
Ambimax [18]	400 mW	MPPT (Hardware)	DLC (22 F) Li-Ion	DC-DC Boost
Enviromote [19]	2.4 W	DC-DC Buck/Boost	NiMH (2x 2.000 mA h)	DC-DC Boost
Dondi *et al.* [20]	500 mW	MPPT (Pilot Cell)	DLC (50 F)	DC-DC Boost
Sunflower [21]	PIN Photodiodes	DC-DC Boost	DLC (0.2 F)	–

With respect to input regulation, a distinction can be made between those architectures that purely regulate voltage level compliance and those that perform maximum power point tracking (MPPT). However, there are even considerable differences in the implementation for each respective group. Taking MPPT implementations as an example, the solutions range from pure hardware implementations to software-based control on dedicated MCUs or the sensor nodes themselves. In individual cases, the input regulation is omitted entirely [14], which requires the careful matching between solar panel and energy storage ratings.

Furthermore, some variations in the implementation of the output regulation and the solar energy converter can be observed. In the majority of cases, the output regulation, if required at all, is implemented in the form of a DC-DC boost regulator. The necessity of an output regulation, however, has been avoided in several cases by selecting a storage technology with a sufficiently high voltage rating or by combining multiple storage cells. In regards to the solar energy converter, the majority of systems utilized solar panels of similar ratings. While a panel with an output power of the order of hundreds of mW appears to be a popular selection, in a few cases, larger and smaller converters have been used, respectively.

In conclusion, there exists a large number of solar energy harvesting systems with different underlying architectures and different component implementations. This number will only grow as development in the research community continues. In the majority of the existing systems proposed in the literature, clear reasoning for the choice of panel rating and energy buffer capacity are not to be found. In order to select the most appropriate architecture and dimension its components for a specific application scenario, clear methods for the comparison and the performance evaluation are required.

2.2. Solar Energy Harvesting Evaluation

Although the number of proposed solar energy harvesting systems is high, a comparative system evaluation has only been performed in a limited manner. In most cases that have been presented in the literature, the proposed solar energy harvesting architecture has been implemented and was evaluated in an application-specific context. This is commonly performed by a laboratory or real-world deployment, which generates the measurement results on the performance of the system.

While this type of result documents the suitability of the architecture for the respective application and its energy demands, it does not allow for a conclusion on the general system performance to be made. As the individual application scenarios, however, have their respective application and location constraints, it is essential to be able to judge a system's suitability also for other scenarios than the one for which the system was initially intended.

Comparative experimental studies are a potential solution, as the performance of multiple systems can be analyzed under the same conditions. There are, however, a number of reasons for an experimental evaluation method to be regarded as infeasible. These reasons include the high cost and time requirements for system reimplementation, the great number of conditions to be tested for, the difficulty of generating these conditions and the continuous development of system architectures.

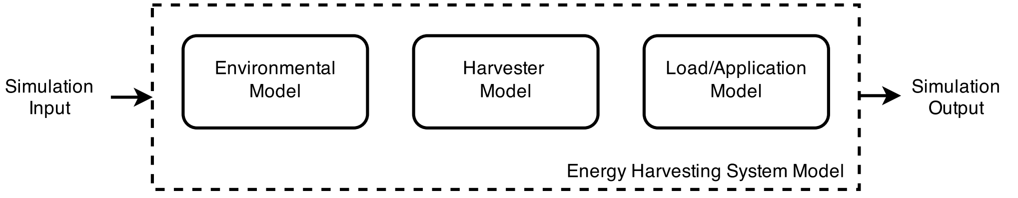
Consequently, solar energy harvesting simulations have been identified as a more efficient method for system comparison and dimensioning. In order for this method to be effective, however, accurate system models are required. In the remainder of this paper, existing methods for solar energy harvesting system modeling will be presented and analyzed. Moreover, we will argue for new approaches for the modeling of energy harvesting circuit architectures.

3. Modeling of Solar Energy Harvesting Systems

Simulations of solar energy harvesting systems are used for various purposes, including the integration of energy awareness in communication and networking protocols, the optimization of the energy harvester design and the prediction of long-term operability, which, in turn, can be used for component dimensioning. Regardless of the individual purpose of the simulation, accurate system models of the energy harvesting system are required for the simulation output to become meaningful. Figure 2 provides an abstracted depiction of the model components that are required for a full energy harvesting simulation. In individual cases, a subset of these model components can be sufficient.

A solar energy harvesting system model principally consists of three components, namely an environmental model, a model of the harvesting unit and an application model. The environmental model describes the amount of available energy in the ambient environment of the harvesting system. In a solar energy harvesting context, this is typically the solar irradiation that will be the input for the conversion technology, for example, a solar panel. While the available energy level in solar energy harvesting scenarios has basic temporal and spatial variations, it is additionally influenced by less predictable factors, such as weather conditions, system setup and physical objects in the surroundings. The application model, on the other hand, describes the energy requirements of the application, which is typically performed by describing the load on the power supply in a statical or dynamical manner. Finally, the harvester model describes how the available energy in the environment is extracted and processed in order to supply the application. This includes the energy conversion and, potentially, the energy buffer that is utilized in the harvesting architecture, as described in Section 2.

Figure 2. Overview of the model components for an energy harvesting system simulation.



3.1. Application Modeling Methods

The modeling of the energy requirements of wireless sensor nodes is not limited to its utilization in the simulation of solar energy harvesting systems. It is generally used to describe the energy requirements of an application and its implementation, which allows, for example, for the comparison of different implementation options to be performed. Any wireless sensor network application requires its nodes to execute a number of tasks (e.g., sensor reading, processing and communication). Each individual task poses a certain energy requirement that is defined by the components involved and the time period that is required for the task execution. The energy requirement of an application can thus be described by the number of times each individual task is performed.

Many environmental wireless sensor network applications follow a sample-and-send structure [24], in which a certain group of tasks is executed in a periodical manner. These time-driven applications are commonly utilized for data gathering purposes. As the same order of tasks is performed in distinct time intervals, the energy requirement of these applications can easily be predicted. The most common approach for describing the energy requirement of an application in these cases is to utilize the duty cycling principle, which provides the continuous average power consumption of the application based on the power levels and time requirements of the involved tasks. In a simplified form, this can be described as:

$$P_{avg} = \delta \cdot P_{active} + (1 - \delta) P_{inactive} \quad (2)$$

where P_{active} and $P_{inactive}$ are the power consumptions during active and inactive periods and δ is the duty cycle of the application, being defined as the ratio of the active period T_{active} to the overall period T:

$$\delta = \frac{T_{active}}{T} = \frac{T_{active}}{T_{active} + T_{inactive}} \quad (3)$$

While Equation (2) only distinguishes between an active and an inactive state, it can easily be extended in order to include each individual task in the model. In this approach, it is upon the user to accurately describe the power levels and time periods for the tasks of the application to be classified.

While time-driven applications are dominant in the design space of environmental wireless sensor networks, event-driven and query-driven applications do occur. A prediction of the exact number of tasks in these scenarios is difficult to be performed, as it depends on the actual number of events and queries. This means that probability parameters have to be included in the modeling of the node's energy consumption, which will introduce a number of uncertainties in the load estimation. A bounding approach would be the common choice in these scenarios, which uses the minimum and maximum number of events, or queries, to be expected in order to estimate the duty cycle.

3.2. Environmental Modeling Methods

In solar energy harvesting, the most important function of the environmental model is the estimation of solar irradiation. Nevertheless, other environmental parameters, such as temperature and humidity, can have an influence on the system performance. Due to the limited investigation in existing methods, we will limit the focus at this stage on the modeling of solar irradiation.

In order to predict solar irradiation, two families of modeling methods are commonly used, namely statistical models and astronomical models. In essence, a statistical model utilizes historic measurements of solar irradiation in order to predict future solar irradiation values. This approach is commonly found in large databases, such as Meteonorm (http://www.meteonorm.com), which collect measurement values of a large number of stations over a long period of time. The collected data is used to predict the solar irradiation to be expected at a location close, or similar to, the measurement points. While this method includes detailed information, such as weather conditions, its accuracy depends on the amount of available measurement locations and the extent of available historic data. Furthermore, variations due to the system setup (e.g., panel orientation and inclination), as well as local obstructions are typically not considered in the database, as this would require an extensive amount of measurement stations. A number of use cases of this approach have been presented in the literature, and improvement methods, for example, in order to include local obstructions, have been proposed [25–29].

An alternative approach is the utilization of an astronomical model. As opposed to the prediction of solar irradiation based on measurement data, the astronomical model calculates the ideal solar irradiation as a function of the angle between the Sun and the solar panel [30]. This angle depends on the solar panel inclination, the panel orientation, the latitude, the time of the day and the day of the year. Although this method can be used to predict ideal irradiation levels at any location in an accurate manner, it does not include any weather conditions or local obstructions. Its main advantage over the statistical model is the flexibility provided by the lacking requirement of historical measurements. Moreover, several improvement methods have been proposed in the literature that extend the basic astronomical model in order to consider non-ideal conditions in the prediction procedure [28,31].

3.3. Harvesting Architecture Modeling Methods

Assuming the knowledge or accurate estimation of the ambient energy levels and the application energy requirements, the solar energy harvesting architecture models are required to describe the transfer of energy from the environment to the load. In order to utilize the simulation results for the selection of an appropriate architecture and its component sizing, the architectural model must be sufficiently accurate to model individual architectural properties.

The modeling methods proposed in the literature can roughly be distinguished between high-level and low-level models. In this, a high-level approach describes the system behavior as a whole, for example, by introducing an energy transfer efficiency between the actual irradiation and the sensor node. These models are typically independent of the actual hardware implementation, but attempt to abstract the parameters of interest with respect to the simulation purpose. As a result, the model can be formulated in an analytical fashion [31,32], which allows for an implementation in computational simulators to be performed in an easy manner. This is of particular interest if the model is used in combination with other analytical models in order to evaluate, for example, energy-aware network protocols or adaptive sampling algorithms. Because this modeling method does not have a direct representation of the underlying architecture, it is important that the abstraction includes all parameters that are required to describe the variations between any architecture to be selected. At the current state of the research, it is difficult to evaluate the existing models on this capability, as the proposed models are only evaluated on single architectures. It appears, however, that there will be difficulties in reflecting the consequences of specific architecture implementation choices, which is required in order to support the selection and dimensioning process in the system design.

Low-level modeling methods, on the other hand, are highly architecture specific. A common method is the modeling of the individual components or modules of which the harvesting architecture is composed. Similarly to the implementation of an electronic system, these component models are then combined into a system model in order to describe the system behavior. The majority of solutions that are presented in the literature are based on equivalent circuit models, which allow for an accurate electrical behavior of the respective components or component modules to be captured. Moreover, this approach allows for existing component models to be reused in order to model new architectures. While the underlying modeling methods remain similar, a number of different implementation methods have been proposed, which range from the derivation of analytical descriptions to the implementation in specific software environments, such as SPICE and Simulink [33–35]. A limitation of the equivalent circuit modeling is the difficulty in accurately describing the behavior of integrated circuits. While the basic components of solar energy harvesting architectures, *i.e.*, the solar panel, supercapacitors and batteries, have well-developed models [36,37], the modeling of integrated circuits is more challenging, as their specific design is usually unknown to the end user. As a result, most systems that have been modeled in this manner are rather simple and avoid the electrical modeling of their integrated circuits. Instead, the behavior of the integrated circuits is simplified, for example, by efficiency factors. This, however, appears to become a challenge for the utilization of this approach, as the number of integrated circuits, and their complexity, increases in solar energy harvesting architectures. In addition, the component-based modeling method requires a great number of measurements to be performed in order to extract the parameters for matching the component models with the actually implemented components [36,37].

4. Data-Driven Architecture Modeling

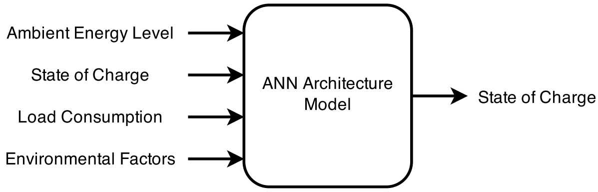
Both of the previously presented architecture modeling approaches possess their individual advantages and disadvantage for usage as support to the architecture selection and component dimensioning problem. While the high-level modeling approach is applied on the system level and, thus, allows for a more flexible adaptation and a faster application, it does not reflect architecture-specific variations and detailed implementation choices. In contrast, the low-level approach is applied on the component level and, thus, provides a high level of detail. As a consequence, the architecture-specific variations and implementation choices can be accurately described by the model, but result in the requirement of a great number of measurements to be performed in order to classify the system to be modeled. For usage in the architecture comparison and the component dimensioning, a generic modeling method is required that can accurately reflect the differences of individual architectures and their components, but, at the same time, is easy to apply to a great number of architectures and implementations. Both modeling techniques, presented previously, require a detailed understanding of the underlying architecture in order to be applied, which hinders their adoption outside of the solar energy harvesting research community. In contrast, we believe that a data-driven approach has the capabilities to accomplish architecture-accurate, but easily-applied, modeling, and we propose that more research be focused on the evaluation of these methodologies.

4.1. State-of-Charge Modeling with Artificial Neural Networks

Data-driven modeling approaches are common in a number of different application areas. Even with respect to solar energy harvesting systems, data-driven approaches are used, for example, in order to predict solar irradiation based on historic measurement values [25,26]. Moreover, data-driven approaches have been utilized in order to capture the behavior of individual components, such as solar panels [38]. A major benefit of artificial neural networks (ANNs) is their capability to learn from existing measurement data and to predict the system's behavior without a detailed understanding of how the system or its underlying function actually look. In a solar energy harvesting context, this can be used in order to capture the behavior of a solar energy harvesting architecture implementation by mapping the significant output parameter to a number of relevant input parameters. Furthermore, this can be accomplished without the requirement of understanding the influence of each individual system component on the output parameter.

For the architecture comparison and component dimensioning, the state-of-charge (SOC) is the fundamental parameter to be modeled. Knowing the state-of-charge of the energy storage element at any moment in time enables the system designer to validate the suitability and performance of an architecture, or its component implementations, for a given application scenario (*i.e.*, the load conditions and the location). Figure 3 depicts a high-level overview of this approach, in which a number of input parameters is utilized by an ANN model to predict the development of the state-of-charge. The most relevant input parameters, in this case, are the current solar irradiation, the current state-of-charge and the current load consumption. However, the method can easily be extended in order to include other input parameters, such as the ambient temperature. In order to generate the model in the first place, a supervised learning approach is utilized, which requires a dataset of the architecture for training purposes.

Figure 3. Overview of the state-of-charge modeling with artificial neural networks.



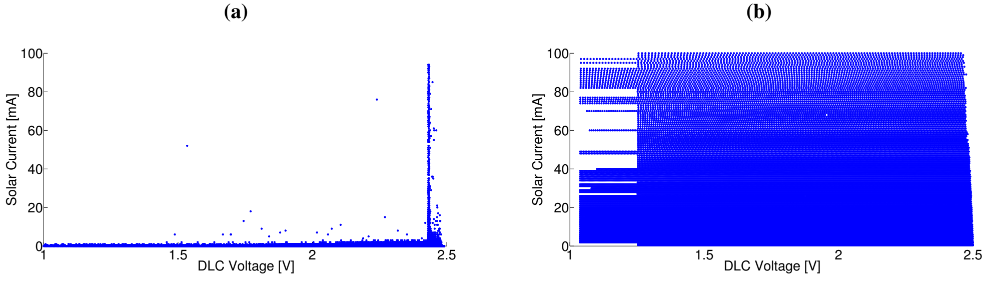
4.2. Training Dataset Generation

The generation of a training dataset for the supervised learning approach can principally occur in two manners. On the one hand, the dataset can be extracted from already gathered measurements (*i.e.*, typically, the measurement results of a deployed architecture); on the other hand, it can be synthetically generated for training purposes.

In the case that an architecture has been deployed previously and has generated a set of measurement values, the utilization of this dataset has the major advantage that no additional measurements have to be carried out. However, the likelihood that this empirical dataset will generate an accurate model is limited, which becomes obvious when investigating the example that is provided in Figure 4a. The figure depicts the distribution of input parameters (*i.e.*, in this case, the input current and DLC voltage) in a two-dimensional space. For simplification, the load consumption and environmental factors are assumed to be constant. Moreover, the input current is used as a representation of the solar irradiation, while the DLC voltage is used to measure the state-of-charge. This example, which contains measurements of over 200 days with a five-minute resolution, indicates that an empirically generated dataset provides only limited coverage of possible input values. While the datasets includes a large number of both the state-of-charge values and the incoming energy, it is more likely that a large amount of incoming energy is observed when the state-of-charge is high. Due to the underlying architecture, which contains a double layer capacitor as its energy buffer element, this is not surprising, because the energy storage is rapidly charged during high irradiation conditions. The resulting distribution of the input parameter combinations, however, will provide training examples for only a subset of the possible input parameters. Therefore, the created model might be inaccurate in describing the behavior of the architecture for untrained conditions.

In order to overcome this challenge, a synthetically generated dataset can be used for training purposes. The main goal of this approach is the generation of a uniform dataset with high coverage of all potential input parameters in an efficient manner. This can be accomplished by using a controlled power source at the input of the architecture (*i.e.*, a controlled light source to bias the solar panel or a controlled current source in order to replace it) and a measurement unit in order to log the resulting effect on the state-of-charge. Figure 4b illustrates the parameter distribution of this approach for one example case. In this case, a controlled current source has been used to generate the input energy parameter, whereas a multimeter measured the state-of-charge development of the DLC. Comparing the two parameter distribution plots in Figure 4, it becomes clear that the synthetically generated dataset provides a much better fundament for the training of the architecture model. Moreover, the dataset can be generated in a highly effective manner, as the bias and measurements can be automated in a laboratory environment. Particularly in the case that deployment results are not gathered previously, the synthetically generated dataset can be obtained in a significantly shorter time period than collecting the required data empirically.

Figure 4. Comparison of (**a**) an empirical training dataset that is extracted from deployment data and (**b**) a synthetically generated training dataset.



4.3. Preliminary Method Evaluation

Initial evaluation results of the proposed ANN modeling method have been obtained using a simple solar energy harvesting architecture. This architecture contains a double-layer capacitor as its energy buffer and has a direct coupling of the solar panel to this capacitor. A current rectification and over-voltage protection is used at the input stage to protect the solar panel and DLC, respectively. The output stage is composed of a DC-DC boost regulator in order to apply a constant supply voltage to the node, even in the case that the state-of-charge is low. For a more detailed description of the architecture, we refer the reader to the work presented in [39].

In order to generate the ANN model, the MATLAB Neural Network Fitting Toolbox is utilized. The underlying model to be trained uses a two-layer feed-forward network with sigmoid hidden neurons and linear output neurons. A Levenberg–Marquardt back-propagation algorithm is used for training. Both, an empirical dataset and a synthetically generated dataset have been used to develop the models, respectively.

For the evaluation purpose, the models have been tested with a dataset of real-world measurements, containing more than 60,000 samples. The evaluation contains a model validation step and a full simulation step. During validation, the capability of the model to predict individual outputs based on input parameters is observed. The predicted state-of-charge is compared to the true state-of-charge based on true input parameters. In contrast, during simulation, the predicted state-of-charge is used as the new input parameter (*i.e.*, estimation errors propagate to the input parameter), which results in a time series of the state-of-charge prediction.

Table 2 gives an overview of the performance of the modeling technique, both for a model created from empirical data and a synthetically generated dataset. Both evaluation steps (*i.e.*, validation and simulation) demonstrate the accurate prediction capability of the models with average percentage errors below 0.1% for validation and below 5% for simulation. Although the amount of small simulation errors increases for the model that has been trained with a synthetic dataset, the overall percentage error is reduced to $< 2\%$. A considerable difference between the validation error and the simulation error can be observed and was found to originate from error propagation. Single significant prediction errors in the model will result in an erroneous input parameter for the next prediction until the model corrects itself. In the architecture under evaluation, this is typically the case when the DLC is fully charged.

Table 2. Overview of the model error distribution for models created from an empirical training dataset (TDS) and a synthetic TDS.

Absolute Deviation	Empirical TDS		Synthetic TDS	
	Validation	Simulation	Validation	Simulation
$[0.1\,\mathrm{V}, 0.2\,\mathrm{V})$	$0.016\,\%$	$2.99\,\%$	$0.013\,\%$	$15.88\,\%$
$[0.2\,\mathrm{V}, 0.4\,\mathrm{V})$	$0.006\,\%$	$2.17\,\%$	$0.003\,\%$	$2.96\,\%$
$[0.4\,\mathrm{V}, 0.6\,\mathrm{V})$	$0.002\,\%$	$1.62\,\%$	$0.002\,\%$	$1.41\,\%$
$[0.6\,\mathrm{V}, 0.8\,\mathrm{V})$	$0.008\,\%$	$1.16\,\%$	$0.002\,\%$	$1.12\,\%$
$[0.8\,\mathrm{V}, 1\,\mathrm{V})$	$0.003\,\%$	$1.01\,\%$	–	$0.35\,\%$
$> 1\,\mathrm{V}$	–	$0.3\,\%$	–	–

5. Conclusions

Solar energy harvesting is a suitable option to prolong the lifetime of environmental wireless sensor networks and can, potentially, lead to perpetual system operation. In order to optimize the solar energy harvesting module for a specific application, however, accurate and time-efficient methods are required. In particular, the selection of a hardware architecture and its component implementation lacks clear approaches to be performed.

In this paper, we have presented a summary of the existing work on solar energy harvesting architectures and their evaluation, which demonstrates the large variety of systems from which to select. Due to the large number of potential architectures, experimental comparison and evaluation methods become inefficient, which leaves system simulation as the remaining approach for the system comparison and dimensioning task. In order for the simulation to meet the accuracy requirements, however, accurate system models must be utilized. We have presented the existing modeling methods for available ambient energy, the energy consumption of the load and the solar energy harvesting architecture itself. Because the harvesting architecture and its implementation is the decisive module for the comparison and dimensioning task, the focus of this work lies in this unit.

A study of the existing methods has shown that the architecture modeling is typically performed in one of two manners. As the first option, the architecture can be modeled on a high abstraction level, which attempts to generate an analytical description of the architecture's behavior on the system level. While this approach allows for a flexible implementation to be carried out and requires only a small number of parameters to be classified, its capability to reflect architectural differences and implementation choices in an accurate manner is uncertain. Alternatively, the architecture can be modeled on a low abstraction level, which includes the modeling of individual components within the architecture. As opposed to the high-level model, the low-level model reflects architectural differences in a more detailed manner, but requires a large number of measurements to be performed in order to classify all parameters.

As a consequence of these challenges, a data-driven approach based on artificial neural networks is proposed for the architecture modeling task. The goal of this model is to provide an accurate, but efficient, method for the description of an architecture's behavior. Using experimentally obtained training data, the model can learn to predict the significant output parameter (e.g., state-of-charge) from a number of input biases and, thus, captures the behavior of the underlying system. The approach has been evaluated in a preliminary study, and the results show that the state-of-charge prediction occurs in an accurate manner with an average percentage error of <0.1% during validation and <2% during simulation. Moreover, the modeling development is highly efficient, as the training dataset generation occurs on the system level (*i.e.*, no classification of individual components is required). Because a detailed understanding of the underlying architecture is not required in order to apply this modeling technique, the approach can easily be automated, which simplifies adoption outside the research community.

Nevertheless, the evaluation of the proposed method has been conducted in a limited scope only. In order to provide a clearer picture on the general applicability of this approach, it must be tested on a variety of system architectures and implementations. Moreover, additional investigations on the influences of the underlying ANN model are required. This includes, for example, the number of layers and neurons used in the network.

Acknowledgments

The authors gratefully acknowledge the financial support of the Energywise project through the European Commission under the European Regional Development Funds.

Author Contributions

These authors have contributed equally to this work.

Conflicts of Interest

The authors declare no conflict of interest.

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PAPER III

Super Article

Abstract

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Introduction

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Acknowledgements

This work was sponsored.

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