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Differential evolution of fuzzy controller for environmentally-powered wireless sensors

M. Prauzek[a,b], P. Krömer[a,b], J. Rodway[a], P. Musilek[a,*]

[a] Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB T6G 2V4, Canada
[b] VŠB – Technical University of Ostrava, 17. listopadu 15, 708 33 Ostrava, Poruba, Czech Republic

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ABSTRACT

Environmentally-powered wireless sensors use ambient energy from their environment to support their own energy needs. As such, they must operate without significant maintenance or user supervision. Due to the stochastic availability of ambient energy, its harvesting, storage and consumption must be managed by an efficient and robust controller that maintains data collection and transmission rates at desired levels, while maximizing the useful operational time of the system. To accomplish this task, the control system must observe the state of charge of an internal energy storage device, and consider the amount of energy available for harvest in the future. At the same time, the complexity of the controller must be limited so that it can be implemented on the simple embedded system of the sensor hardware. This paper presents a comprehensive synthesis of desired behavior of such controllers, and describes procedures for their design and optimization through an evolutionary fuzzy approach. The main contribution is the formalization of design objectives and development of the fitness function that drives the optimization process. Additional contributions include a comprehensive evaluation of several soft computing optimization approaches, thorough analysis of the optimized controller, its comparison to baseline control strategies, and validation of its operation with real energy availability forecasts.

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1. Introduction

Wireless sensors and sensor networks [2] are often used for long-term environmental monitoring applications that take place in remote, inaccessible locations with variable ambient conditions. These environmental monitoring systems must be capable of reliable autonomous operation, and independent of externally supplied energy or human intervention. To achieve this level of self-sustainability, such systems are usually powered by energy harvested directly from the deployment environment [9]. Design of environmentally-powered wireless sensors is a complex problem with a number of conflicting goals and several design and implementation constraints [59]. The most common concerns include desired sensor sampling rates and acceptable delays between data transmissions.

Wireless sensor devices are usually designed as low-power embedded systems with a low-performance microcontroller unit (MCU) that cannot implement computationally extensive control algorithms [50]. At the same time, the complexity of the control algorithm affects the overall power consumption of the system [7]. In addition, the algorithms must be fault tolerant to satisfy the stringent requirements for autonomy and dependability. Many existing approaches include conventional rule-based algorithms [66] implemented using state machines [26] or heuristic control methods [48]. The system proposed in this article uses fuzzy control that is easy to design and implement on limited hardware, and able to deal with imprecise or missing data. The optimization method of differential evolution is then used to adapt the fuzzy control system to match the planned deployment environment for best performance. The application-specific fitness function used for optimization of the fuzzy control system is an important contribution of this work.

The dependence of environmentally-powered devices on the ambient energy suggests the possibility to use energy availability prediction to estimate the state of charge of energy storage devices [12], to improve the device performance [46], or to reconfigure the entire system [39]. In this contribution, prediction of energy available over a time horizon serves as an additional input to the fuzzy energy manager. The proposed approach is illustrated through the process of predictive fuzzy controller design. It extends

* Corresponding author. Tel.: +1 780 492 5368.
E-mail addresses: michal.prauzek@vsb.cz (M. Prauzek), pavel.kromer@vsb.cz (P. Krömer), jrodway@ualberta.ca (J. Rodway), petr.musilek@ualberta.ca (P. Musilek).

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previous studies by the authors on optimization of fixed parameters of wireless sensor nodes [37] and on optimization of a simple fuzzy controller without energy prediction [36]. The structure of the predictive controller is first devised manually, considering the nature of the energy management problem. The controller parameters are then optimized using differential evolution and three other soft computing methods. Strong emphasis is placed on a comprehensive evaluation of the evolved complex, predictive control strategy.

The performance of such an extended fuzzy controller is thoroughly tested through a series of simulation experiments based on an accurate hardware model of a wireless sensor node and energy availability data measured at the intended deployment site. Such experiments can provide useful information about energy management strategy performance, in a short time and at a low cost. Given the realistic models and data used in the simulations, it is reasonable to expect that the developed controllers will be applicable in a real deployment environments. They also serve to determine the optimal length of the prediction horizon. The best performing controller is then tested using real forecasts of energy availability, rather than historical measurements. Testing results confirm validity of the proposed approach and the practical value of predictive energy management for environmentally-powered wireless sensors.

This paper is organized into six sections. Section 2 provides a brief overview of the state of the art in energy management for wireless sensors and in evolutionary fuzzy systems. Section 3 a model of the optimization problem, including synthesis of energy management strategies and design of corresponding fuzzy logic controllers. Section 4 then details controller optimization by several soft computing methods, concentrating on differential evolution. Results of simulation experiments are described in detail and discussed in Section 5. The final Section 6 brings major conclusions and outlines possible directions for future work.

2. Related work

2.1. Energy management in wireless sensors

Wireless sensor networks (WSNs) are composed of a large number of wireless sensor nodes deployed inside, or in close proximity of, an area of interest [2]. Such sensor nodes are implemented as embedded systems with multiple functions, including sensing, data management, and wireless communication. They can be placed in remote locations with limited access and without energy infrastructure. To allow their sustained operation under such conditions, wireless sensor nodes are often powered using ambient energy harvested from their deployment environment [9,20,23,46,59], leading to so called environmentally-powered wireless sensor nodes (EPWSN). Energy harvesting (EH) reduces the environmental footprint of sensor nodes [63], contributes to their energy neutrality [62], and eventually leads to perpetual networks [20].

The efficient use of EH systems requires sophisticated energy management and control [63]. This involves both the node level (e.g. adaptive duty cycling [67,69] and task scheduling [27,56]), and the network level (e.g. media access control, routing, and time synchronization protocols [59]). It is a complex optimization problem with a simple objective: to maintain data sensing and transmission rates at desired levels, while maximizing the useful operational time of the system through optimal energy harvesting and consumption [63]. It must consider the properties of particular ambient energy sources (such as stochasticity and periodicity) [35], as well as the requirements of the application domain (such as robustness, reliability [5,68], and communication throughput [35]).

Various adaptive energy management strategies have been proposed for EH system control. They can be classified as local (when each node considers only local information), global (when actions are selected based on assumed complete knowledge about the entire network), and hybrid approaches that combine both [27,68]. In general, they can use information about the state of node hardware (e.g. remaining energy level [67]), heuristic information (e.g. expected usage of monitored rooms [27]), assumptions based on historical information (e.g. average amount of ambient energy available at certain location and time), or predictions (e.g. forecasting energy consumption and harvesting [63,69]). Many recent studies have concluded that predictive strategies lead to a better utilization of available ambient energy [27,46,56,63,67,69].

2.2. Evolutionary design of fuzzy systems

Artificial evolution is a well-established approach to design and optimization of intelligent systems [4,17]. Biologically inspired methods have been identified as a tool suitable for construction and tuning of accurate and interpretable fuzzy systems [17]. Differential evolution (DE) is a relatively recent evolutionary method noted for its simplicity, ease of use, good performance, and an excellent track record of real-world applications. In the last decade, DE has been used also to tailor different types of fuzzy systems [16,22,38,43,44] and neural-fuzzy systems [14,32,70] for various application [28,49].

Cheong and Lai [16] proposed the use of the DE as a part of automated design of hierarchical fuzzy controllers. The optimization algorithm was used to coordinate the outputs of subcontrollers within the hierarchical system and to optimize rule base templates. The validity and usefulness of this approach was evaluated on the classical cart-pole (inverted pendulum) control problem and it was shown that DE is a valuable method for design of symmetrical fuzzy controllers.

Another work by Eftekhari et al. [22] used DE for constructing interpretable fuzzy inference systems. More specifically, it was used to simplify fuzzy models initially generated from data by subtractive clustering and to optimize centers and widths of fuzzy membership functions of the simplified system. The proposed method used an interpretability measure to express the fitness of the system under simplification, and mean squared error as a measure of accuracy in the final step.

The evolution of fuzzy rule-based meta-schedulers for grid computing by a DE-inspired approach is due to [49]. The evolved control system used Mamdani-type fuzzy rules with Gaussian membership functions. The traditional DE was modified for this application. Every fuzzy rule was encoded as a DE vector and the entire population represented the rule-base, following the Michigan approach well-known from the domain of genetic fuzzy systems [18]. The study showed that the proposed method outperformed traditional learning strategies (i.e. the Pittsburg approach). The optimized meta-scheduler was better, in terms of training fitness, than simple scheduling strategies.

The study of [28] showed the ability of DE to tune fuzzy controllers for financial market modelling. It evolved encoded membership functions and fuzzy rules using a problem specific version of DE and showed that such optimized controller is able to embrace the complex, non-linear, and dynamic nature of the problem and that the evolved models are able to optimize market portfolio return for different types of markets and different portfolia.

Oh et al. [43] suggested the use of adaptive DE for optimization of a cascade fuzzy controller, and evaluated it on a variant of the traditional inverted pendulum problem (rotary inverted pendulum) and ball and beam system. Although focused on the evaluation of the proposed DE parameter adaptation strategy, the work also provided a clear evidence that DE is a method suitable for fuzzy controller optimization, outperforming other evolutionary approaches such as genetic algorithms.

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