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High-level modeling and synthesis of smart sensor networks for Industrial Internet of Things☆

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ABSTRACT

In this work, we use a high-level design methodology for the rapid hardware synthesis of a complex smart sensor network (SSN) system. The GRAFCET is then used to model the individual functional modules and the hierarchical behavior of the system. The behavior of each module is represented as a sequential–concurrent hybrid discrete event system. We apply high-level synthesis rules to generate a VHSIC hardware description language (VHDL)-target efficient hardware for a smart sensor controller and smart gateway controller. Finally, these embedded hardware controllers are generated automatically to integrate all intelligent functional modules into a complex embedded system, and a hardware circuit is then synthesized. The experimental results show that the hardware circuit can meet the definition of an SSN system for Industrial Internet of Things applications. Moreover, this methodology enables a coherent design quality, short design period, low development cost, and short time-to-market for complex industrial applications.

1. Introduction

Smart sensor network (SSN) systems show promise for building powerful Industrial Internet of Things (IIoT) applications. IIoT refers to the close integration of computation, networking, communication, and devices, and it is characterized by sensing, inferring, actuating, information exchange, data storage, and data processing capabilities.

A wide range of SSN applications have been developed in recent years, in which smart sensor devices are embedded in interconnected devices to sense, monitor, measure, communicate, and exchange information. This enables the collection, processing, analysis, and dissemination of valuable information gathered in various industrial environments.

SSN systems offer the ability to perform computations, make intelligent decisions and control industrial equipment to promote the progress of the enterprise or manufacturing unit [1–3]. Fig. 1 shows a generic model of an SSN system for industrial applications.

Most industrial SSN systems include a large number of smart sensors, actuators, gateways, electronic devices, and industrial equipment connected to the Internet or a cloud server for industrial environments. An industrial SSN system can be considered as a physically interconnected network because an increasing number of devices are equipped with smart sensors, electronic devices, and industrial equipment [5], in which things can be connected and controlled remotely.

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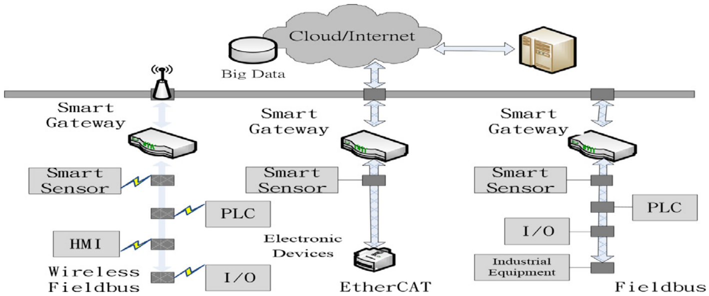

Fig. 1. SSN system for industrial applications.

Smart sensors must sense, exchange information, transmit useful collected information, and automatically assign roles to manage, deploy, and schedule the behaviors of industrial devices over a network. In an industrial SSN system, different things have different communication functionalities. A gateway must be able to facilitate the communication or interaction of various devices; furthermore, it must connect up to the cloud and down to smart sensors and existing controllers embedded in the network system. Consequently, smart sensors and gateways [6,7] play a crucial role in IIoT applications.

The authors of [2–4] have proposed that future industrial SSN systems should have characteristics such as self-configuration, self-optimization, self-protection, and self-healing because smart sensors will become more intelligent. In this paper, our definition of an SSN system for IIoT applications involves the following functionalities: nonlinear calibration, self-compensation, self-inspection, self-validation, and self-diagnosis.

Several field-programmable gate array (FPGA)-based implementations of SSN systems have been proposed for when high performance is required in the targeted IoT applications [11–18,23,24]. The potential benefits of FPGAs are mainly due to the high speed, super parallelism, and flexible configuration that can be achieved for high-performance operation. Hence, these hardware solutions generally overcome the low effectiveness, low efficiency, high power consumption, and slow response time of microprocessor-based software solutions [24].

To understand the development of SSN systems in industry, this work summarizes the foundational technologies of SSN systems and their key challenges, and identifies research constraints and system requirements. The significance and contribution of this manuscript are summarized as follows:

Generic hardware synthesis with embedded intelligence in things is difficult to achieve because most methods are applicable to hardware synthesis with a single function and sequential state transition, and they lack multiple functions, concurrent state transitions, and branching state transitions. Therefore, the main contribution of this manuscript is the focus on hierarchical modeling and designing. Embedded smart multiple functions satisfy SSN system requirements and are suitable for the behaviors of industrial SSN systems. We provide an effective and efficient hierarchical discrete-event modeling methodology by using hierarchical design, behavioral modeling, and automatic hardware synthesis to realize the interconnection, intercommunication, interaction, and interoperation requirements of a complex SSN system.

Therefore, a complex SSN system is decomposed into coarse-to-fine submodules, and each independent submodule is considered as a discrete-event system (DES). For each independent DES, we present a complete VHSIC hardware description language (VHDL) synthesized code to translate into a VLSI hardware architecture circuit for a smart sensor and gateway controller.

On the basis of research and development, this work focuses on a consistent and systematic design methodology using the GRAFCET language. Complex embedded system design and hardware synthesis tasks are straightforward and effective. Because of the hierarchical design, behavioral modeling, and automatic hardware synthesis paradigm, the SSN hardware controller is endowed with composability and software reusability instead of complexity. This reduces the development time and cost as well as the procedure of traditional trial-and-error approaches.

The rest of the paper is organized as follows: In Section 2, we explain our proposal and discuss related studies. In Section 3, the foundational technologies of SSN systems and their key challenges are summarized, and the research constraints and system requirements are identified. In Section 4, the effective and efficient hierarchical discrete-event modeling methodology is introduced in detail. Moreover, the benefits of using a consistent and systematic design methodology based on the GRAFCET language are discussed. Section 5 demonstrates the SSN design details, namely function and behavior definition, hierarchical modular design, discrete-event modeling, and high-level synthesis. Experimental results are presented in Section 6. Finally, in Section 7, the main conclusions of the work are explained and the limitations of the research are discussed.

2. Related work

In this section, we initially present an overview of SSN based on FPGA technology, followed by the state of the art SSN systems of several study cases and their application environments. Numerous recent studies have used FPGA in the design of SSN systems to improve the processing system performance [3,11–18]. Those researchers have proposed developing