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A novel green software evaluation model for cloud robotics☆

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ABSTRACT

The energy consumption of cloud robotics is an important design factor to be considered early in system development. Software as the main enabler of cloud robots, its energy consumption will directly influence the energy consumption level of the entire system. In this paper, we propose a green software model for cloud robotics based on energy consumption time state transition matrix (ETSTM), which can effectively integrate the logic functions, energy consumption, and execution time of software into a single model. To improve the practicability of ETSTM, we provide a software energy consumption function based on software characteristic fitting by a backpropagation (BP) neural network, which can be used to predict software energy consumption. Furthermore, we provide two types of energy consumption analysis algorithms based on explicit execution path search and bounded model checking (BMC) for ETSTM. The experiment results show that the proposed method can achieve good performance.

1. Introduction

Recently, with the rapid development of some emerging technologies like the Internet of Things (IoT) [1–3], cloud computing [4,5], and industrial wireless networks [6–9], etc., a strategic initiative called "Industrie4.0" was proposed and adopted as a component in the German government's "High-Tech Strategy 2020 Action Plan" [10,11]. In the stage of "Industrie4.0", cloud robotics will play an important role [12,13]. However, cloud robotics consumes large amounts of electrical power resources. The design quality of software, as the main component of cloud robotics, will produce effects on the energy consumption of the whole system directly. Therefore, the green evaluation of software has become a focal point in academic and industrial fields.

The green evaluation of software is able to verify whether the software satisfies the design constraints of execution time and energy consumption when given specific input and output behaviors. In general, there are two methods used in the green evaluation of software: the measure method and the model evaluation method [14]. The measure method is suitable for the situation that the software development has been completed, which can analyze the amount of energy consumption more accurately, however, unable to judge whether the green indication have a bottleneck and also locate the bottleneck. The model evaluation method, such as formal verification, can predict and analyze the green indication, and then locate the bottleneck and provide an important reference to improve the software performance. In fact, the software designers prefer to know whether the green indication meets the design constraints rather than get the exact value of energy consumption.

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Thus, the model evaluation method may be a better choice in some cases. With appropriate design model and analysis method, the energy consumption of cloud robotics software can be predicted and considered in the early phase of the development.

State transition matrix (STM) is a table-based modeling method to specify the behaviors of embedded systems, which has been used widely in embedded fields, especially in robotics design and automotive electronics. According to a survey carried out by Japan Embedded System Technology Association (JASA, http://www.jasa.or.jp), 45% of respondents have been using STM as a design method [15]. However, STM model lacks the semantics of energy consumption, which makes it unsuitable for the green evaluation of cloud robotics software.

To solve the limitation of STM and carry out green evaluation for cloud robotics software, we put forward a novel green software model and its analysis method. The main contributions of this paper are as follows:

(1) We propose a novel green software model called energy consumption time state transition matrix (ETSTM) which expands the semantics of energy consumption for STM by adding the energy consumption function.
(2) We give a specific method to fit the energy consumption function by using a backpropagation (BP) neural network, which can improve the practicability of ETSTM and be convenient for the developer to predict the energy consumption at the software design stage.
(3) We provide two types of energy consumption analysis methods based on explicit execution path search and bounded model checking (BMC) for ETSTM, which can give a variety of perspectives for the green evaluation of software.

The rest of this paper is organized as follows. Section 2 introduces the work related to our method. Section 3 gives the related definitions of ETSTM. Section 4 presents the energy consumption prediction method for software. Section 5 proposes the green evaluation algorithm for the ETSTM model. Section 6 shows the modeling and analysis detail for a type of intelligent cloud sweeping robot, and analyzes the effectiveness and efficiency of our method. Finally, the conclusion is given in Section 7.

2. Related work

The main idea of present paper is to extend the formal semantics of STM, which makes it suitable for the green software modeling of cloud robotics. To the best knowledge of the authors, our approach is the first energy consumption semantics expansion for STM. However, some scholars used other existing software models to perform green evaluation by semantics expansion.

Shin [16] discussed a formal analysis method for the software energy consumption by providing two formal notations, the PCA (Power Consumption Automaton) and the fWLTL (Linear Temporal Logic with freeze quantifiers). Then the logic model checking is used to verify the energy consumption constraint problem. Senn et al. [17] provided an early multi-level energy consumption model for embedded software based on AADL (Architecture Analysis and Design Language) design flow, and designed an energy evaluation tool PET. After that they illustrated their approach with the energy consumption model of PowerPC 405. Zhang et al. [18] proposed a green software architecture model based on energy consumption TPN (Time Petri Nets), which introduced an energy consumption transfer function into TPN. Further more, they provided the evaluation method for the energy consumption TPN model, and analyzed the trustworthiness problems of CPS (Cyber Physical Systems) software influenced by the energy consumption. Kang et al. [19] figured out the limitations of energy consumption semantics in EAST-ADL (Electronics Architecture and Software Technology Architecture Description Language) by extending energy consumption constraints and integrating this extension with formal modeling and analysis techniques. Moreover, they provided a mapping method for automatic model transformation between the extended EAST-ADL and priced timed automata. Finally, the energy consumption of software can be analyzed by model checking. Marinescu et al. [20] also provided a similar modeling method based on EAST-ADL and implemented their model on UPPAAL [21], which is an excellent model checker for timed automata. Then they analyzed the energy consumption of software by using SMC (Statistical Model Checking) on UPPAAL. Zhu et al. [22] proposed a method to model and analyze software energy consumption of real-time embedded system based on Priced Timed CSP (Communication Sequential Processes), which is a semantic extension for Timed CSP by adding price information. The energy consumption of software can be mapped into the price of Priced Timed CSP. Afterwards they provided the optimal path algorithm to find the minimum energy consumption path between two reachable states.

There are still some disadvantages to the above-mentioned research. With regards to the modeling method, the energy consumption modeling method is still simplex, and the inherent relationship between the structure of the software and the energy consumption is separated, which limits the practicability of the model. With regards to model analysis, the path-based method cannot analyze the energy consumption under the constraint of multiple functional properties because of its limited capacity. In addition, the analysis method based on model checking has a stronger analyzing capacity, but when there are multiple variables in the model, the state space explosion problem will appear.

3. Definitions of the ETSTM model

ETSTM is the formalized semantic expansion for STM by adding the energy consumption function for each cell of STM. The energy consumption function can be used to predict the energy consumption of the source code within the cell. The