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A web service-based approach for developing self-adaptive systems☆

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ABSTRACT

The current development on self-adaptive systems mainly focuses on autonomy and self-containment where decision-making solely depends on the local knowledge base within the system. This limits the evolution of the knowledge base for making more precise decisions. There have been some recent works using the cloud for the knowledge base. However, they suffer from the overhead caused by the communication with the cloud. In this work, we propose a hybrid approach for developing self-adaptive systems using both the local knowledge base in the vehicle and the global knowledge base provided via a web service. The global knowledge base is shared and evolves by multiple vehicles through the web service. We validate the approach using Gazebo, a 3D simulation environment for robotic systems. The results show 96% precision in identifying objects with a viable overhead introduced by the web service and 40% improvement in precision over the traditional approach.

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1. Introduction

Self-adaptive software systems have gained an increasing attention along with the evolution of the robotics domain and smart computing. A core component in a self-adaptive system is the knowledge base which provides the foundation for making an adapting decision for a given situation. The knowledge base is often designed to be self-evolving, learning from the past decisions and effects. However, the current development mainly focuses on autonomy and self-containment where decision-making solely depends on the local knowledge base within the system. This limits the evolution of the knowledge base, which consequently causes a negative impact on the quality of decisions. More recently, several researchers have looked into using the cloud for the knowledge base of self-adaptive systems (e.g., [1–3]). However, their works are limited by the overhead introduced by the communication with the cloud, which is critical for real-time systems.

In this work, we present a hybrid approach for developing self-adaptive systems using both the local knowledge base in the vehicle and the global knowledge base provided via a web service. In the approach, we use the local knowledge base for making an initial decision to identify an encountered object. If the object cannot be identified, we use the global knowledge base through a web service which is shared by multiple self-adaptive units through the web service for collaborative evolution to make more mature decisions. We use supervised learning based on k-Nearest Neighbors (kNN) [4] in the local and global knowledge base. In addition, we use unsupervised learning based on k-means clustering [5] in the global knowl-

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edge base for handling unknown objects. We implemented the approach using Robot Operating System (ROS) [6] which is a software framework providing operating system-like functionality for developing robotic software. For web services, we use Generic Simple Object Access Protocol (gSOAP) [7] which is a software development toolkit for Simple Object Access Protocol (SOAP) applications. We evaluated the implementation using Gazebo [8] which provides a 3D simulation environment for robotic systems. The evaluation is carried out for four different scenarios with the results of each scenario analyzed in terms of precision and response time. The evaluation shows 96% precision in identifying objects with a viable overhead introduced by the web service, and 40% improvement in precision over the traditional approach using only the local knowledge base with no extra knowledge gathered from external entities.

The remainder of the paper is organized as follows. Section 2 discusses the related works on developing self-adaptive systems. Section 3 describes the web service-based approach. Section 4 discusses the implementation of the approach. Section 5 presents the evaluation of the approach. Section 6 concludes the paper with discussions on the future work.

2. Related work

The work by Magee and Kramer [9] on dynamic modeling of software architecture has inspired many subsequent works (e.g., see [10–12]) on feedback loops which are essential for the evolution of self-adaptive systems. However, the feedback mechanism in these works is often kept hidden or abstract. IBM Autonomic Computing Architecture [13] introduced an open architecture for self-adaptive systems that consists of monitoring, analyzing, planning, and executing components which are known as MAPE standing for Monitor, Analyze, Plan and Execute.

Garlan et al. [11] presents a set of conditions for monitoring environmental properties (e.g., network latency) for a system to dynamically adapt to environmental changes. A condition is defined in terms of operations and repair strategies specific to an architectural style. The conditions are specified on the architectural level for generality and simplicity. However, their approach is limited in learning and adapting to a situation that is not considered in the conditions.

Wang et al. [14] presents a machine-learning approach for developing a multi-robot system where a group of intelligent robots works cooperatively to transport an object to a goal location in a dynamic environment. Their approach integrates reinforcement learning (RL) with genetic algorithms (GAs) to increase the precision of system behaviors. However, RL and GAs are slow in performance in adapting to a dynamic environment, which imposes an inherent limitation on their approach. Furthermore, the overhead introduced by the integration offsets the benefits from the integration on precision. They also present a modified Q-learning algorithm for making a decision when conflicts are encountered in resource use or behaviors.

Dorigo et al. [15] present an approach for developing behavior-based robots using multiple classifier systems running in parallel in a hierarchical structure. Each classifier system learns simple behaviors through interactions with the environment. The hierarchical organization distinguishes two learning activities, one for learning behavioral sequences and another for learning coordination sequences. Classifier systems at the lowest level in the hierarchy learn behavioral sequences which are real actions activated by sensory input from the environment. Only the classifier systems at the lowest level have direct access to the environment via the sensors and actuators of the robot. On the other hand, classifier systems at a higher level learn to coordinate the activities of classifier systems at lower levels. Their work is modular, allowing more classifier components to be added to learn more behaviors. However, that is at the expense of increased resource consumption.

More recently, several researchers (e.g., [1–3,16]) propose to use cloud computing as a base platform for the knowledge base of robotic systems. The use of the cloud enables a robotic system to be more scalable and efficient, while allowing it to be lighter and smaller in size. This also improves the performance of identifying objects by the increased maturity of the knowledge base shared and contributed by multiple robotic units through the cloud.

Kuffner et al. [1] introduced the use of a cloud-based knowledge base for collecting and analyzing information about an encountered object and determining robot behaviors in response to the object. The knowledge base receives a feedback from the robot on every interaction with the object. The knowledge base may benefit other robots facing the same experience. Unlike our work using a two-level decision process, their approach solely relies on the cloud for determining robot behaviors.

Liu et al. [2] proposed a cloud-based architecture for distributed robotic information fusion systems to offload computation to the cloud. The architecture is based on ROS, consisting of one master controlling multiple robots simultaneously in the network where the master is loaded into a virtual machine. In their approach, a failure of the ROS master causes the halt of the entire system, which raises a reliability concern. Unlike their approach, we allow a self-adaptive unit to have its own local knowledge base, which enables the system to continuously run even in the case where the web service is unavailable for any reason. Similar to Kuffner et al.'s work [1], they also offload image processing into the cloud. However, relying solely on the could for image processing introduces significant communication overheads.

Guoqiang et al. proposed a cloud-based architecture for robotic systems to enable the extension of the computation and information sharing of robots on a network [16]. The architecture leverages the combination of an *ad-hoc* cloud formed by machine-to-machine (M2M) communications among participating robots and an infrastructure cloud enabled by machine-to-cloud (M2C) communications. However, it is not clear how the architecture can be validated as there are no details on implementation and experiments.

Chen et al. [17] introduced the concept of "Robot as a Service (RaaS)" which is an all-in-one design for the service provider, service broker, and service client to support robot services performed remotely in different places, which reduces

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