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A modular design of Bayesian networks using expert knowledge: Context-aware home service robot

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ABSTRACT

Recently, demand for service robots increases, and, particularly, one for personal service robots, which requires robot intelligence, will be expected to increase more. Accordingly, studies on intelligent robots are spreading all over the world. In this situation, we attempt to realize context-awareness for home robot while previous robot research focused on image processing, control and low-level context recognition. This paper uses probabilistic modeling for service robots to provide users with high-level context-aware services required in home environment, and proposes a systematic modeling approach for modeling a number of Bayesian networks. The proposed approach supplements uncertain sensor input using Bayesian network modeling and enhances the efficiency in modeling and reasoning processes using modular design based on domain knowledge. We verify the proposed method is useful as measuring the performance of context-aware module and conducting subjective test.

1. Introduction

Recent robot researches have shifted the attention from industrial robots to service robots. According to the report of Japan Robotic Association (Fig. 1), robot market with personal and service robots as the center will grow exponentially in the near future. Since personal and service robots are investigated and made in order to provide services to individual users, they should have intelligence for various goals (Garcia, Jimenez, Santos, & Armada, 2007). For this reason, much research for robot intelligence appears from all over the world.

European Union investigated 73 million Euros in 74 projects with the topic of "Cognitive Systems and Robotics," and it covers various topics of intelligent robotics including object recognition, cognitive architecture, activity modeling, planning, learning and adaptation (European Commission ICT Research). Researches on robotics in United States tend to seek practicality, and they include robot intelligence. Robotics Institute in CMU have studied service robots for people with reduced functional capabilities due to aging or disability (Brose et al., 2010), and personal robots group in MIT Media Lab have studied robots that can express their emotion and learn social interaction (Breazeal, Gray, & Berlin, 2009). Japan is in a dominant position in personal service robot field. In Japan, major companies such as Sony, Honda, and NEC as well as a government conducted related research projects. Sony's AIBO and Honda's ASIMO are well-known to the public as well as robot researchers, and they have been provided to major research groups as platforms for robot intelligence (Hing et al., 2008).

Despite much effort to implement robot intelligence, most of them focused on low-level control and recognition problems. We construct probabilistic model so that service robots in home environment can provide context-aware services to users and use modular design approach based on domain knowledge for efficient modeling. Bayesian networks are used to handle uncertain and various input values reliably. Bayesian network models are modularized and designed based on services and functionalities for efficient modeling and reasoning processes, and each module with functional independence can be used together if necessary.

The rest of this paper is organized as follows: Section 2 describes the backgrounds and related works on context-aware services in three different domains and general Bayesian network modeling, and Section 3 presents Bayesian network modeling approach based on modular design and the case study of context-aware home robot services. Section 4 evaluates the proposed modeling method in terms of performance and user satisfaction, and Section 5 concludes this paper and discusses future works.

2. Related works

2.1. Context-aware service

Context can be defined as any information that can be used to characterize the situation of an entity such as a person, place, or

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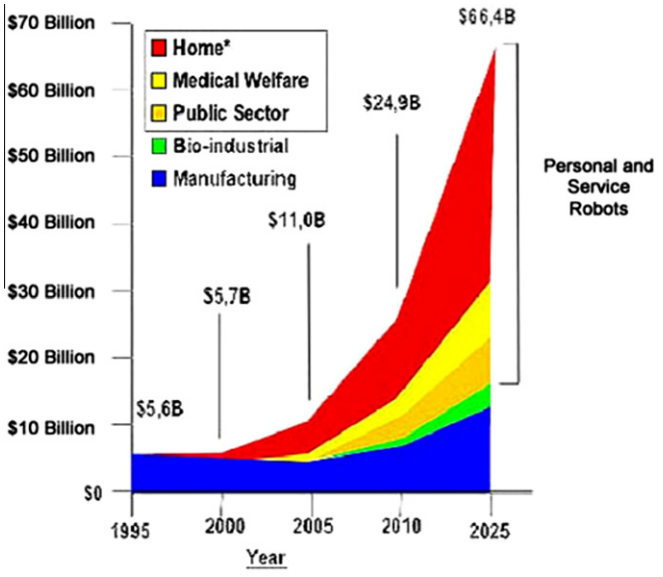

Fig. 1. Estimation of robot market in Japan. Source: Japan Robotic Association.

object that is considered relevant to the interaction between a user and an application (Dey, 2001). Context-aware services are to recognize context and to provide services that are appropriate to with the recognized context (Kwon & Choi, 2009). They are becoming more important as research in mobile and pervasive computing grow. In this situation, this paper summarizes the related works on context-aware service in three different service domains: mobile computing, robotics and a smart home.

Context-awareness in mobile computing is more important than in others because user context changes more dynamically, so many groups have studied mobile context-awareness. Raento et al. developed a software platform for context-aware mobile applications called ContextPhone (Raento, Oulasvirta, Petit, & Toivonen, 2005), and Eagle and Pentland referred user profile as context, and presented a social match making service called 'Serendipity' with that platform (Eagle & Pentland, 2005). Siewiorek et al. presented a context-aware mobile phone called SenSay that adapts to dynamically changing environmental and physiological states (Siewiorek et al., 2005). It used a state diagram to recognize busyness of users and set a mode of mobile phone automatically. Panagiotakis and Alonistioti presented an intelligent distributed framework that enables the dynamic service composition for mobile applications (Panagiotakis & Alonistioti, 2006). With an advancement of recent smart phone technology, application areas of context-awareness in mobile computing have extended. Buttussi and Chittaro developed MOPET, a wearable system that supervises physical fitness activities in outdoor environment (Buttussi & Chittaro, 2008). Yap *et al.* presented a context-aware augmented city guide using various global and local features (content) and recognized landmarks (context) together (Yap, Chen, Li, & Wu, 2010). Based on recognized landmark information as context, they performed more accurate recognition and provided better service. Therefore, context-aware services using mobile phone is very diverse and covers context from low- to high-levels.

On the other hand, studies on high-level context-awareness in robotics have not been conducted very much even though those in service robot have been conducted actively. Most of them focused on image/vision processing, hardware control, or recognition of low-level activities. In the European project of "Cognitive Systems and Robotics," the COGNIRON (Cognitive Robot Companion) develops cognitive robots whose purpose would be to serve humans as companions, so they would be able to learn new skills and tasks in constant interaction with humans (Germa, Lerasle, Danes, & Brethes, 2007). It targets three robots and demonstrations: The robot home tour, the curious robot, and learning skills and tasks. The MORPHA project is to equip intelligent mechatronic systems like service robots with the capability to communicate, interact and collaborate with human users (Ehrenmann, Zoellner, Rogalla, & Dillmann, 2002). The iCub is a humanoid robot platform developed and provided for the RobotCub, an open project of human cognition study (Vernon, 2008). The PlayMate is to develop intelligent robots that perform sophisticated interaction with objects in human environments as manipulating objects, learning properties and interacting with humans (Stark, Lies, Zillich, Wyatt, & Schiele, 2008). These projects focused on implementation of cognitive systems mainly with human–robot interaction and covered recognition of low-level context such as gesture, position and movement. The URUS (Ubiquitous Networking Robotics in Urban Settings) project focused on implementing a network of robots in urban environment and covered high-level context such as emergent situation of user/robots based on networked sensors as well as low-level context like simple human activities (Tardioli, Mosteo, Riazuelo, Villarroel, & Montano, 2010).

Recent smart home projects also include context-aware services. The AMBIENCE project targeted context-aware indoor environment based on low-level context recognition of hand gesture and human location (Markopoulos, Mavrommati, & Kameas, 2004). The UKARI project presented a real-life validation experiment facility simulating a future residence equipped with diverse sensors and network connected home appliances (Tatsuya et al., 2007). It includes an interactive robot called Otaku and provided context-aware service using activity inference based on rule and learning.

Though some of these works provided high-level context-aware services, the proposed context-aware service based on probabilistic modeling is different from these works. The URUS project targeted urban environment, not home environment, and they used networked robots. We assumed an independent mobile robot that worked in home environment. We also did not use ubiquitous home and ubiquitous sensors because they are not general home environments available in the near future. Based on these assumptions, we implemented context-aware services for home robot based on modular design of Bayesian networks. Table 1 summarizes the related works on context-aware projects/services in three different domains described previously.

2.2. Bayesian network modeling

Bayesian network has emerged as a powerful technique for handling uncertainty in complex domains (Ejsing, Vastrup, & Madsen,

Table 1
Related works on context-awareness in three domains (mobile, home and robot).

Project/ author	Service domain			Low-level context recognition	High-level context-awareness
	Mobile	Home	Robot		
ContextPhone	○	×	×	○	Δ
Serendipity	○	×	×	○	○
SenSay	○	×	×	○	○
Panagiotakis et al.	○	×	×	○	○
MOPET	○	×	×	○	○
Yap et al.	○	×	×	○	○
COGNIRON	×	○	○	○	×
MORPHA	×	○	○	○	×
iCub	×	×	○	×	×
PlayMate	×	×	○	○	×
URUS	×	×	○	○	○
AMBIENCE	Δ	○	×	○	×
UKARI	×	○	×	○	○