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Modeling indoor lighting inspection robot behavior using Concurrent Communicating Lists

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ABSTRACT

Today, energy efficiency is one of the top priorities in building design and construction. A significant share of energy usage is due to indoor lighting. Although methods exist for design and control of intelligent lighting systems, the task of real-world lighting assessment and verification remains only partly addressed. This paper describes foundations for design of a robot to conduct regular and automated audits of lighting quality in office buildings, with emphasis on the modeling of its behavior. The proposed model uses the *Concurrent Communicating Lists (CCL)* notation, which allows it to be easily simulated, executed, and formally verified. The *CCL* behavior model is discussed in the context of *Knowledge-Behavior-Platform (KBP)* robotic architecture proposed as a practical model runtime environment.

1. Introduction

Recent regulations and development of smart energy solutions have influenced the design and construction of buildings in many ways. Among them are efforts to minimize heat dissipation by the use of modern insulation materials as well as automation systems which allow greater control over practically all features of a building. However, one aspect of energy usage is ubiquitous and inevitable: interior lighting. This problem persists both in newly constructed buildings and in those which already exist. Numerous methods have been developed for design as well as control of intelligent lighting systems (Pan, Yeh, Chen, Lin, & Tseng, 2008; Singhvi, Krause, Guestrin, Garrett, & Matthews, 2005), but one aspect remains only partly addressed: real-world assessment and evaluation of indoor lighting. This task is crucial in new buildings as well as those being adapted, but it is more demanding in the latter group, as it is necessary to both assess the existing solution and verify the effects of modifications. These tasks are usually performed by a human inspector equipped with a special device (such as a luxmeter). However, in large areas this can be extremely time-consuming and prone to errors. Therefore, the need arises for autonomous, robot-based indoor lighting assessment. Such solution seems to be even more attractive, due to the fast-increasing affordability of even sophisticated robotics platforms. The construction industry also is trying to take advantage of the popularity of robots. Typical applications of a civil infrastructure robot are automation of road (Peyret, Jurasz, & Zekri, 2000), bridge and tunnel inspection (Murphy et al., 2011; Oh et al., 2009), pipe inspection (Lu, Huang, Yan, & Cheng, 2007), power plant inspection (Breitenmoser, Tâche, Caprari, Siegwart, & Moser, 2010) etc. In building construction (Khoshnevis, 2003), primary applications include building assembly, building skeleton erection, interior finishing etc. (Gambao & Balaguer, 2008; Zavadskas, 2010). Also, intelligent robotics tries to contribute to development of construction research (Belohoubek & Kolibal, 1996; Lowe, 1990); however, compared with the traditionally understood automation, it still seems underrepresented. One of the reasons for this is the uncertainty of what the robot will do in environments which are often not fully controlled (Lowe, 1990). Questions arise such as what autonomous behavior is and how to react to unforeseen circumstances. The answer may be a proposition of a robotic system which provides better insight into the possible behavior of the robot. Understanding of an autonomous robot behaviour, ability to model how it works, and the capability of formal verification of the model maximize the chances of creating a product that meets the customer's needs. This observation led the authors to propose the new 3-tiered *KBP (Knowledge-Behavior-Platform)* robotic architecture (Fig. 1). It is designed to give the user possibility to model, verify and execute the behavior of a robot. *KBP* integrates the high, deliberative knowledge layer with the low-level hardware platform by plugging them into single unit – a behavior model written in *CCL (Concurrent Communicating List).* Since the *CCL* notation is derived from process algebras and primarily focuses on executable modeling of concurrent systems (Kułakowski & Szmuc, 2012), it allows users to write a control program in a special Lisp-like notation

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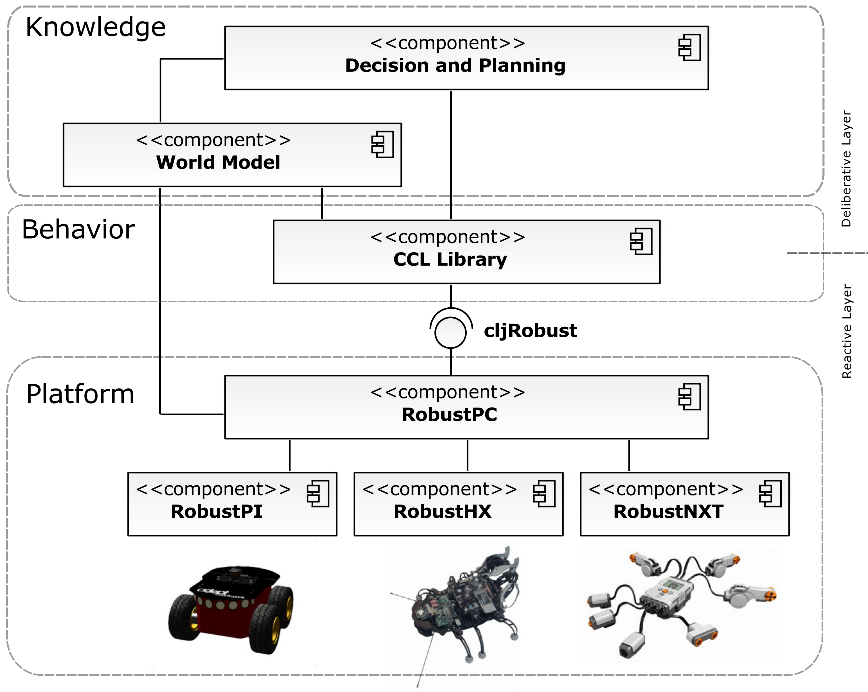

Fig. 1. KBP architecture – component perspective.

and run it step by step in simulation mode, perform formal verification or execute it like a regular computer program. The usefulness and effectiveness of this approach is demonstrated on the example of a lighting inspection robot behavior model, which is verified both formally and by means of simulation. The choice of the lighting inspection robot case-study was well thought out. Indoor lighting in households, offices, industrial and sport areas, etc., is a key element in providing visibility. That, in turn, influences numerous factors important to humans, such as task performance, mood and atmosphere, visual comfort, aesthetic judgement, health, safety and well-being, as well as social communication (Rea, 2000). Lighting standards have been developed in order to provide guidelines which specify minimum light levels for various types of applications.

The article is composed of five sections. After the first introductory section, a brief outline of AI robotic architectures is presented. The third section provides basic information about lighting measurements, and introduces the principles of *CCL* notations. The forth section presents the lighting inspection robot behavior model and discusses the problems of model verification, simulation and further development. The last section discusses the benefits of the presented architecture and summarizes the work.

2. Architectural background

When discussing robotics systems, the following three major architectural styles in AI robotics need to be mentioned:

- Hierarchical Planning and Control Architecture,
- Reactive/Behavior Based Control Architecture,
- Hybrid Architecture.

Proponents of the first approach (Albus model (Albus et al., 2002)) emphasize planning and knowledge processing combined with the usage of a *world model* reflecting the current state of knowledge about the system's environment. The second architectural paradigm – the reactive/behavior based control approach – focuses on behavior generation and real-time response to the stimuli coming from the surrounding environment. Instead of using a world model and sophisticated planning algorithms, it postulates to sense the state of the environment and then decide what to do next (Brooks, 1987). The *Subsumption Architecture* proposed by Brooks is one of the most influential representatives of this approach. Due to its intuitiveness and simplicity, it resulted in a number of models and implementations (Groves, Collins, & Gini, 2009; Rai, Kook, & Hong, 2010; Risler & von Stryk, 2008; Zhang, Zhang, & Qin, 2009).

The third, hybrid approach tries to combine the advantages of its predecessors. Its proponents point out that the two previous approaches in fact perceive the same phenomenon from different perspectives and, as such, complement each other. The *AuRA* (Long, Hanford, & Janrathitikarn, 2007) system may serve as an example of this architectural style.

The proposed *KBP* architecture is a hybrid approach. It tries to integrate decisional knowledge and the hardware platform by plugging them into the behavior component. According to this approach, all the operations that require a real-time response, like wheel speed control or halting the platform when the bumper is pressed, are implemented in the hardware platform layer. Soft real time actions, like halting the platform when an obstacle is detected by a range sensor, as well as simple planning actions, can be handled via the behavior/control layer. The top, deliberative layer is responsible for long-term planning and reasoning, and supports the behavior control layer in taking control decisions. The proposed KBP approach is an example of the 3T (3-Tiered), *Hybrid State-Hierarchy* architecture (Murphy, 2000), where the middle-tier (referred to (Murphy, 2000) as a *sequencer*) has a well defined form provided by *CCL*.

The created behavior model is partially verifiable i.e. it is possible to verify all the temporal properties of the model in isolation from the state of the knowledge and the hardware platform. The *KBP* approach is "behavior-centric", which means that the behavior specification is in the focus of the people involved in the project. Specifying the behavior of a robot determines the specification of