Engineering Applications of Artificial Intelligence 57 (2017) 16–37

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

A study on metadata structure and recommenders of biological systems to support bio-inspired design

Sun-Joong Kim, Ji-Hyun Lee*

Graduate School of Culture Technology, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea

ARTICLE INFO

Keywords:
Bio-inspired design
Biological system metadata modeling
Knowledge-based system
Recommendation system
Ontology

ABSTRACT

Bio-inspired design was introduced as an alternative method to encourage breakthrough innovations during design projects by stimulating analogical reasoning and thinking of designers. However, the method did not perform as well as researchers expected because most designers, who are novices in the fields of biology and ecology, cannot infer the proper analogue (i.e. biological system) from nature. To resolve this fundamental problem, a causal model based representation framework for 'analogical reasoning' – searching and selecting the biological systems to apply – have been developed. In addition, ontology based repository structures and retrieval systems have been proposed to support 'analogical thinking' of designers. Nevertheless, these systematic approaches still restrict the candidates and inevitably lose potential biological systems relevant to the design project, due to the '*physical relation*' biased problem and the ambiguity of the indexing mechanism of both current representation frameworks and retrieval systems. For example, the causality based support system known as a robust representation framework for a single biological system, stores information of a biological system only by its internal '*physical relations*' and retrieves biological systetabms only by the physical relevance. However, from the perspective of ecological thinking, the further relatedness of '*physical, biological, and ecological relations*' composes the holistic concept used to identify an organism in the flow of evolution because the '*biological and ecological relations*' are also involved in the traits that designers may be interested in. Therefore, the supplementary information for '*biological and ecological relations*' must be added to index the biological and environmental interactions, and to use the connectivity among entire organisms in the retrieval process. In this research, a causality based holistic representation framework for biological systems and an 'all-connected' ontology based repository and retrieval system are developed as a knowledge-based recommendation system to support bio-inspired design. The knowledge-based system we developed allows engineering designers to search and select a particular *biological system* and extract *design strategy* without much biological knowledge. This effort provides more opportunities in a bio-inspired design process by adding potential biological systems that might previously not have been considered.

1. Introduction

Breakthrough innovation during a design process occurs when designers bridge two knowledge pieces that share similar contexts which have never been connected before (Hon and Zeiner, 2004; Lindermann and Gramann, 2004; Herstatt and Kalogerakis, 2005). This process of knowledge transfer is referred to as analogy, and the task of analogy has been emphasized to promote design creativity by systematic methods such as *synectics*, the *lead user method*, *TRIZ*, and *bio-inspired design* methods (VanGundy, 1981; Terninko et al., 1998; von Hippel et al.,1999; Lindermann and Gramann, 2004; Herstatt and Kalogerakis, 2005). Among these methods, the bio-inspired design method has come to the fore since it directly accesses various design strategies of diverse scales through inspiration from millions of analogues, specifically, biological systems (BSs) (VanGundy, 1981; Chakrabarti et al., 1992; Chakrabarti and Tang, 1996; Vogel and Davis, 2000; Bonser and Vincent, 2007; Sarkar and Chakrabarti, 2007; Yen and Weissburg, 2007; Mak and Shu, 2008). However, frustration in selecting a particular BS and extracting design strategies from the chosen BSs is inevitable for most designers, because of their insufficient biological knowledge (Herstatt and Kalogerakis, 2005; Helms et al., 2009; Stroble et al., 2009; Nagel, et al., 2010; Sartori et al., 2010; Cohen et al., 2014; Feng et al., 2014; Nagel, 2014; Vandevenne et al., 2014). For this reason, in the context of bio-inspired design, there is a critical need for a system to support the tasks that require abundant biological knowledge (Herstatt and Kalogerakis,

* Corresponding author.
E-mail addresses: iuvenalis@kaist.ac.kr (S.-J. Kim), jihyunlee@kaist.ac.kr (J.-H. Lee).

http://dx.doi.org/10.1016/j.engappai.2016.10.003
Received 11 August 2016; Received in revised form 5 October 2016; Accepted 6 October 2016
0952-1976/

2005; Chiu and Shu, 2007; Helms et al., 2009; Stone et al., 2014; Vandevenne et al., 2014). Specifically, bio-inspired design support systems were developed to help designers in selecting BSs in nature as analogues and extracting design strategies from the chosen BSs without academic domain dependence (Herstatt and Kalogerakis, 2005; Chiu and Shu, 2007; Glier et al., 2014; Kim et al., 2015).

Reflecting on the design process of bio-inspired design, previous bio-inspired design systems can be grouped into 1) 'analogical reasoning' tools that target the design phases for the selection of BSs (analogues) and 2) 'analogical thinking' support methods that target the design phases for the design strategy extraction and application (Helms et al., 2009). First, the 'analogical reasoning' tools have been developed to systematically support the task of analogue (BS) selection (Helms et al., 2009; Stroble et al., 2009; Nagel, et al., 2010; Sartori et al., 2010; Cohen et al., 2014; Feng et al., 2014; Nagel, 2014). Here, the prior rule for the selection is the contextual similarity between the design problem and the biological characteristics of BSs (Nagel, et al., 2010; Sartori et al., 2010; Nagel, 2014). In particular, reasoning tools have been developed as retrieval systems that operate the BS search algorithms designed for the particular BS repository (Chakrabarti and Tang, 1996; Vattam et al., 2008; Yim et al., 2008; Helms et al., 2009; Wilson et al., 2009; Vattam et al., 2010; Goel et al., 2012; Chakrabarti, 2014; Vincent, 2014). However, the scarcity of '*biological relation*' knowledge at the BS repository causes restricted search activity by the designers. For instance, designers may retrieve the *African mound-building termites* by '*physical relations*' which make a base of the present repositories. Currently, most systems cannot print out relevant organisms such as the relative *termites* that share a comparable '*physical relation*' with the *African mound-building termites*. The problems in repository construction are responsible for this limitation; specifically, the current representation frameworks are the origin of the limitation because the frameworks allow BS information to be stored only by the '*physical relation*' of BS (Nagel, et al., 2010; Jacobs et al., 2014; Stone et al., 2014; Vincent, 2014). Therefore, improvement of the BS representation framework is necessary to resolve this fragmentary issue.

Second, further studies that support the 'analogical thinking' tasks of designers have been carried out (Helms et al., 2009; Cohen et al., 2014). Here, the 'abstraction' for the design strategies of BSs has been recognized for the high level of contribution in assisting the tasks of design strategy '*extraction*' and '*application*' which influence design creativity (Vincent and Mann, 2002; Mak and Shu, 2004a; Mak and Shu, 2004b; Vincent et al., 2006; Mak and Shu, 2008; Cheong et al., 2011; Goel et al., 2012; Cohen et al., 2014; Feng et al., 2014; Shu et al., 2011; Vincent, 2014). The specific abstraction schemes have borrowed from the '*physical relation*'-based BS representation frameworks; for example, the traditional '*function-behavior-structure (F-B-S)*' model or *TRIZ* method was utilized (Vincent and Mann, 2002; Vincent et al., 2006; Cohen et al., 2014; Vincent, 2014). When these two abstraction schemes are used to abstract potential design strategies of a BS, the '*F-B-S*' model abstracts the design strategy of BS into a '*function-behavior-structure*' composition and the *TRIZ* method abstracts it into one of the design principles (Vincent and Mann, 2002; Vincent et al., 2006; Cohen et al., 2014; Vincent, 2014). However, the critical problem of the '*physical relation*' biased schemes is that these schemes make it difficult to apply diverse design strategies of various scales during 'analogical thinking'. Practically, if a BS is not exactly matched with the design problem in terms of '*physical relation*', it might catalyze 'analogical thinking' of designers if the BS has considerable ecological characteristics. This catalysis is very influential to enhance the expected design novelty of the design outputs (Mak and Shu, 2004a; Mak and Shu 2004b; Mak and Shu, 2008; Srinivasan and Chakrabarti, 2010; Chakrabarti, 2014). For example, the design strategy of *T cell* might be a good analogue for the design problem of a security system even though the analogue has a different physical scale with the problem. This is because the analogue has a similarity in behavioral characteristics with the problem; the design strategy at a cell-scale in terms of defense reflects the design strategy at a society-scale. Unfortunately, the current abstraction methods cannot deliver the ecological behaviors of the BS because the indexing mechanism for '*ecological relation*' in the abstraction schemes is not obvious or is absent (Chakrabarti, 2014). Therefore, in summary, improvement of the '*biological relation*' and '*ecological relation*' for the design support system is needed to retrieve relevant BSs that are 1) biologically related and hence might have comparable characteristics and 2) behaviorally or ecologically related and hence might cause creative knowledge transfer in a BS application.

In this research, the recommender of BSs (i.e. biological ideas) that holistically retrieves the considerable alternatives in the BSs for a design problem is newly developed. For the recommendation, the relativeness between the design problem and the BSs is quantified in the holistic perspective of '*physical, biological, and ecological relations*' through the developed ontology structured retrieval system. The originality of this research can be summarized by the following reasons:

- To expand the limited data quantity of the BSs, the developed method retrieves the un-stored organisms – the organisms not stored in the current retrieval system – from nature using a newly developed algorithm that translates the biological characters of systematics to design strategies.
- To resolve the '*physical relation*' biased problem of the current systems, the newly designed holistic representation framework allows designers to retrieve the '*biologically and ecologically related*' alternatives that were disregarded when the retrieval was only based on '*physical relations*'.
- To support both the 'analogical thinking' and the 'analogical reasoning' that bio-inspired designs require, the research proposes a novel recommender with a suitable representation framework and a retrieval algorithm. In more detail, the design strategies of BSs which are the design principles ('analogical thinking') are explicitly represented through a causal model, and the recommendation of BSs ('analogical reasoning') is possible using a causal model based ontology with holistic relations.

To achieve the research goal, the representation framework is complemented by systematic indexing mechanisms and a causal model based ontology. The packaging work of the retrieval system accompanies 1) construction of the representation framework and the repository of BSs, 2) definition of the reasoning mechanisms for the un-stored organisms using the *identification keys*, and 3) development of the indexing mechanisms and the following algorithms for similarity assessment. The objectives and tasks for the groups are explained in sequence below.

First, the representation framework that represents biological characteristics in a holistic ecological approach is developed. The holistic approach refers to the ecological thinking that covers the '*physical, biological, and ecological relations*' to represent the biological characteristics of BSs. On the basis of the holistic approach, the causal model based representation framework for a BS is constructed using the internal relations of the '*physical relation*', '*biological relation*', and '*ecological relation*'. The *SAPPhIRE* causal model (Chakrabarti, 2014) is redesigned for the representation framework; the data indexing schemes are defined for each element of the redesigned causal model. The biological characteristics of BSs are also collected and stored using indexing schemes; the raw data of BSs are collected from *AskNature* (Deldin and Schuknecht, 2014) web.

Second, the reasoning mechanism for un-stored BSs is developed. Specifically, the mechanism translates the structured data of *identification keys* to biological characteristics using a latent semantic meaning analysis. When the expected system retrieves relevant BSs, this mechanism is used to explore organisms un-stored in the repository.