Title:
A Data-driven Biological Knowledge Representation and Recommendation Approach for Biologically Inspired Design Enabled by the Five-dimension Model

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Introduction:
Nowadays, the advance of information communication technologies especially the enabling technologies for Industry 4.0 have brought new techniques and methods to refine the domain of engineering design [1]. In turns, these technologies have brought about both new challenges and opportunities to development of Biologically inspired design (BID)[2-3]. To be specific, there are growing requirements for products with the smartness, the sustainability and other features that lead to more complex design tasks. On one hand, design wisdoms extracted from the nature hold huge potential to provide numerous prototypes with new features such as the smartness and the sustainability, on the other hand, ever-growing complex of design requirements asks for more effective knowledge process techniques to retrieval and recommend appropriate biological prototypes before being transformed into design schemes.

BID closely depends on knowledge transformations from the biological domain into engineering design [4]. BID approaches are usually built on knowledge representation model, through which to facilitate the inter-domains knowledge transformations. Therefore, an effective biological knowledge process approach is based on suitable knowledge representation. There are many previous studies have proposed various knowledge representations to model biological prototypes in BID, such as the Design -analogy to nature engine (DANE) [5]and the State-action-place-physical-organ-input-environment (SAPPhRIE)[6]. Both representations depend on the manual computation to model biological prototypes based on perspectives of the functional characteristics, the function-behavior mapping characteristics. Variants of these function-based biological knowledge representation methods are also workable for inspiring smart product design. However, these knowledge representation methods are in short of providing effective ranking algorithms to recommend appropriate biological prototypes to meet complex design requirements. In this study, a data-driven biological representation and recommendation approach is proposed to smooth the creative design through BID in industry 4.0. To do so, a variant biological knowledge representation method is firstly proposed based on both the function-based idea and the five dimensions framework designed for the digital twins [7]. Through the proposed representation approach, biological prototypes and their inspired bionics results are connected through multiple dimensions relations. Built on those relations from different dimensions, correlations between engineering design requirements and biological protypes with their inspired bionic solutions can be calculated, then biological prototypes with high scores can be recommended to engineering designers as appropriate ones for inspiring BID. As results, the proposed approach can improve the adaptability of BID in product innovations in the new era of

Industry 4.0 by saving the labor of engineering designers in searching of suitable biological prototypes to be analogized as well as finding exiting examples about how to transform biological prototypes into innovative solutions to multiple design requirements.

Main Idea:

The proposed approach mainly includes three sections:

The first section is a variant BID knowledge representation, which is built on basic ideas of the function-based modeling and five-dimension model from the digital twin, aiming at containing knowledge about biological prototypes and their inspiring engineering solutions. Therefore, users of the proposed approach who usually come from engineering domain can reach not only knowledge about how biological prototypes work but also knowledge about how these biological prototypes had been transformed and used in real engineering design schemes.

The second section introduces the data-driven self-updating strategy of the proposed BID knowledge representation. In the proposed knowledge representation model, all its subsections can be renewed with new data being inputted. As an open BID database, amounts of biological prototypes and bionic engineering solutions will increase with continuously efforts from various contributors.

The third section will expound an algorithm of recommending appropriate biological prototypes to solve required engineering design problems. The proposed algorithm uses multiple norms besides the functional similarities aiming to match biological prototypes according to the overall ideality that considers indicators such as the environment sustainability, building costs and adaptability.

Afterwards, an illustrative example of design for bionic wind power blade is used to address the feasibility of the proposed BID knowledge representation and recommendation approach.

- A variant BID knowledge representation based on the framework of five-dimension model

It is the framework built on the five-dimension model from the digital twins that differs the proposed BID knowledge representation approach from other exiting representations such as the DANE or SAPPhRIE. The five-dimension model for the digital twins was firstly proposed by Prof. Tao to organize complex constitutions of the digital twin in engineering domain [7]. Afterwards, the five-dimension model has been widely applied in architecting, simulation and optimizing of engineering system through the digital twins [8-9].

The framework of the five-dimension model is shown as Fig.1, which consists of five parts: Physical entity (PE), virtual entity (VE), services, digital twin data (DD) and connection. To be specific, the PE stands for the real engineering system, while the VE includes information on facets of geometry, physical, behavior and rules to describe the corresponding PE. Service involves both functional service and business service to meet needs from both inner and outer users. DD stands for the digital twin data involving specific data from sections of PE, VE and service, as well as other knowledge data and fusion data. Connection plays the role of the bridge to connect different sections, which are mainly in forms of data channels.

A variant BID knowledge representation is proposed by this study by adopting to the framework of the five-dimension model from the digital twins. In the proposed BID knowledge representation, there are five sections by referring to the five dimensions, which aims at putting all kinds of knowledge related to BID together for engineering designers. Fig.2 is the framework of the proposed variant BID knowledge representation.

In Fig.2 there are five parts in the proposed BID knowledge representation by referring to the five-dimension model in the digital twins. Correspondingly, the biological prototype takes the place of the physical entity, which includes biological prototypes with potential to inspiring engineering design, while the engineering solutions play roles of virtual entities containing information about engineering design schemes that have been inspired by biological prototypes. The former DD section is replaced by the BID database which includes specific information about how biological prototypes and engineering solutions realize their functions, as well as their function structures. The function set replaces the former service section that involves main functions, assistant functions and auxiliary functions extracted from both facets of biological prototypes and engineering solutions. The connection section is kept in the proposed representation to indicate correlations between two other sections, which contain mapping and data sharing strategies.

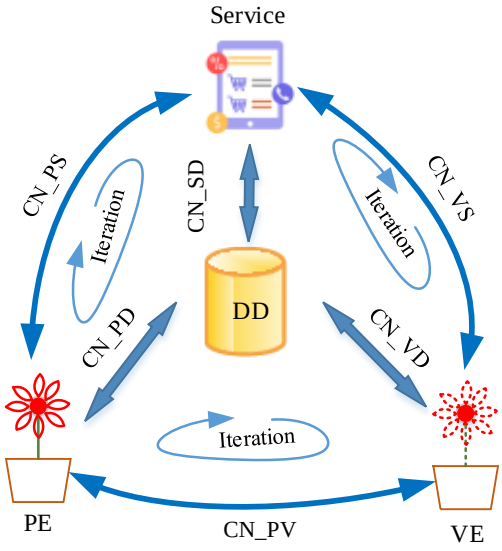

Fig. 1: The traditional five-dimension model for the digital twins.

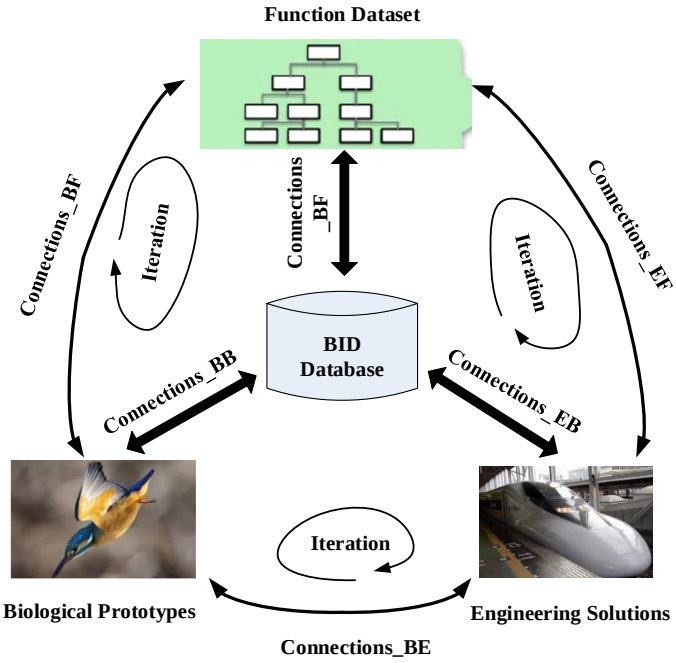

Fig. 2: The framework of the proposed BID knowledge representation.

There are several evident features of the proposed BID knowledge representation compared with existing modeling methods such as the DANE and SAPPhRIE. First of all, the proposed representation method can present information from both biological prototypes and bionic engineering design schemes, which is help engineering designers understand long-range analogies in the transformation from biological prototypes into engineering solutions. On the second place, the proposed knowledge

representation approach provides an effective way to accumulate BID knowledge, therefore, engineering designers can find various biological prototypes and exiting bionic engineering solutions related to their design problems, which is useful for inspiring creative ideas. Thirdly, bionic engineering solutions also contains important information about how to realize biological function in engineering applications.

- The data-driven self-updating strategy of BID knowledge database

Different sections in the BID knowledge representation are correlated through different types of connections. Therefore, a database built on the proposed BID knowledge representation holds a wide range connected knowledge graph. Since the proposed BID knowledge database is designed for collaborative innovations, self-updating strategies are important for its workability. There are two main strategies to facilitate the self-updating of the BID database. The first one is the inspiring data inputting strategy, which requires data builders to consider and make decision about all kinds of connections when they input new information into the database. The second one is the iteration strategy which decide degrees of correlations based on inputting results from multiple contributors during the collaborative design.

Specifically, Fig.3 illustrates the basic mechanism of the inspiring data inputting strategy. Refers to Fig.3, database builders usually start from inputting biological prototypes data to inputting engineering solutions by following five steps. At the step of inputting BPs, New connections between the BPs and BID databases is created by asking builders to provide the biological knowledge about prototypes to be inputted. In the second step, builders are required to model functions of BPs and analyze the importance of each function unit in BPs, meanwhile connections between the BPs and the FSs are updated by builders' analysis. At the third step, builders are required to input all the function units with their importance values into the BID database. At the fourth step, builders need to input information about functional models of biologically inspired engineering solutions and indicate the importance of each function unit. Therefore, connections between the ESs and the FSs can be updated based on builders' remarks. At the fifth step, builders are required to input application information about engineering solution to be inputted with the purpose to create new connections between the ESs and the specific information about their bionics features, meanwhile, connections between the BPs and the ESs are then updated.

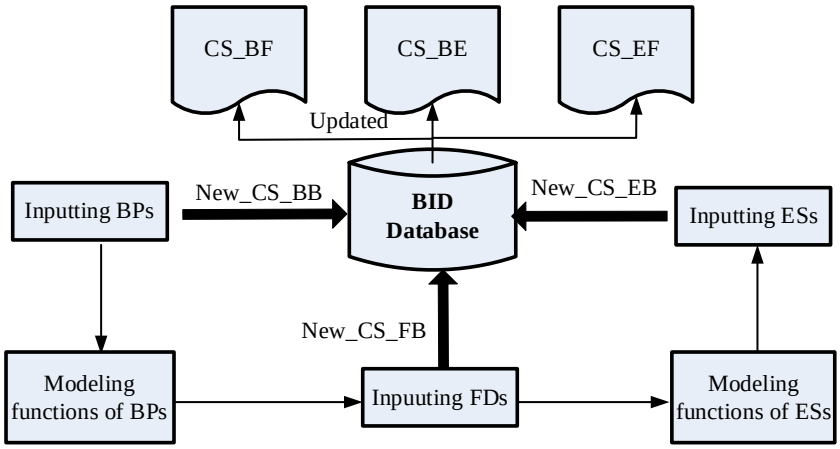

Fig. 3: The workflow of the inspiring data inputting strategy.

The iteration strategy closely depends on collaborations of multiple contributors. With more information contributed by different builders, more reasonable connections in the proposed BID knowledge database will formulate. All the connections in the database have strength values which range from 0 to 1 to indicate the reliability. Calculation of each strength value depends on the frequency of positive remarks from contributors.

- The algorithm to recommend analogical prototypes for BID

Based on the proposed BID knowledge database and the self-updating strategies, algorithms to recommend analogical prototypes in BID to smooth the long-range knowledge transformation from biological domains to engineering design. However, exiting algorithms only recommend biological prototypes to meet engineering design requirements using functional similarity, such as the Asknature which is one of the most popular online knowledge sources for BID. Previous studies ever revealed that knowledge about former successful BID cases is helpful for engineering designers to build their own creative solutions, since the generation of creative ideas is a typical case-based reasoning (CBR) process.

The proposed recommending algorithm is able to provide three kinds of knowledge to facilitate the long-range analogies in BID. The first kind knowledge is appropriate biological prototypes that can meet main engineering design requirements which are usually in forms of functional characteristics. The second kind of knowledge recommended by the proposed algorithm is engineering solutions found in exiting products, patents and science documents those origin from matched biological prototypes. Knowledge on the third facet mainly contains key enabling technologies for the realization of biological prototypes in engineering applications.

- Case study

An exemplar design for bionic wind power blade is used to show how the proposed BID knowledge representation and recommendation approach is applied in the real BID practice.

Conclusions:

This study intents to present a new variant biological knowledge representation based on the principal framework of the five-dimension model from the digital twins. Compared with exiting representation methods, the proposed approach has a data-driven feature to facilitate the self-updating of BID knowledge database. Therefore, the algorithms can be developed to recommend biological prototypes, related engineering solutions and enabling technologies for BID to smooth the long-range analogies from biological knowledge into engineering design.

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