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Biomimetics — Ontology-Enhanced Thesaurus (OET) for biomimetics

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Foreword

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This document was prepared by Technical Committee ISO/TC 266, *Biomimetics*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

A thesaurus is often used to map terms between different knowledge domains. The Knowledge Infrastructure for Biomimetics project was established to fill the gap between biology and technology. The project originally planned to develop a biomimetic thesaurus and an ontology that would complement such a thesaurus in situations where the thesaurus cannot deliver useful search terms because concepts in the two domains are associated with keywords that lack explicit links. Although work on the biomimetic thesaurus has been postponed, Ontology-Enhanced Thesaurus (OET) does not require a thesaurus and can be used as a standalone tool. For more details see 5.2.

OET addresses a portion of this knowledge infrastructure. It is composed of an ontology of biomimetics and an application named Keyword Explorer that provides an interface to the ontology. OET and Keyword Explorer help designers, engineers, and other bio-inspired design (BID) practitioners by mapping technical terms to biological terms that can then be used to search biological texts to identify biological models (see Figure 3). For example, a traditional thesaurus may relate “stain-resistant” to “self-cleaning” or “soil release”. A biomimetic thesaurus or internet keyword search may additionally return “antifouling”. OET can identify organisms that share functions related to “antifouling” but not directly associated with the term.

In Clause 4, after a brief overview of the current state of the art of tools and systems in biomimetics, OET and Keyword Explorer are positioned in the related work. Clause 5 describes OET together with its design rationale. In-depth description on the implemented ontology in OET is Clause 6 and Clause 7. Clause 8 describes accessing and running the Keyword Explorer prototype in order to get feedback from readers.

NOTE A publicly available version of Keyword Explorer and OET is available at http://biomimetics.hozo.jp/OET/demo.html as a web application — it only includes one function (antifouling) but demonstrates the capabilities of the prototype version. The corresponding ontology can be inspected via “Browsing the Biomimetics Ontology” in http://biomimetics.hozo.jp/OET/, but it is not possible to download it. Paid users of this document can download the prototype version.

Biomimetics — Ontology-Enhanced Thesaurus (OET) for biomimetics

1 Scope

This document describes prototypes of the Ontology-Enhanced Thesaurus (OET) and the Keyword Explorer interface to OET. Although their design philosophy is described, this document focuses on their value and how they work.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
data
minimum piece of information that is meaningful for its potential readers or users

Note 1 to entry: In many cases, data is a component of larger entity, a data set or a data base. Data can be text as in research papers, simulation models, algorithms, numbers, pictures, figures, voice and video recordings.

3.2
database
set of almost any digital objects, which can be text, picture, sound, video, etc.

3.3
information retrieval service
set of software that allows users to retrieve information from *databases* (3.2)

Note 1 to entry: Quite often, ontologies or thesauri are incorporated in the information retrieval service.

3.4
index
set of key terms (usually arranged in alphabetical order) with pointers to the original source of each term (includes books, research papers, or other forms of writing)

3.5
metadata
data (3.1) that provides information about other data

Note 1 to entry: The keywords in an index are metadata of the body of the text from which the keywords are extracted.

3.6
ontology
formal, structured, and explicit description of concepts in a domain of discourse and the relations between them in the fields of knowledge management and artificial intelligence

Note 1 to entry: An ontology together with a set of individual instances of classes constitutes a knowledge base.

3.7
taxonomy
orderly classification of things or concepts into groups within a larger system, based on common qualities

3.8
thesaurus
list of words arranged in groups based on similarity of meaning

4 Role of the knowledge infrastructure for biomimetics

4.1 General

In Figure 1, ISO 18457 and ISO 18458 cover the phases from “Analysis” to “Overall evaluation” and ISO 18459 covers the phases from “Project/design of experiment” to “Prototype construction/manufacturing.” The Knowledge Infrastructure for Biomimetics covers “Analysis” and “Analogy/abstraction”, with OET focusing mainly on “Analogy/abstraction”. OET is a product of the Knowledge Infrastructure project and is composed of an ontology and the Keyword Explorer interface.

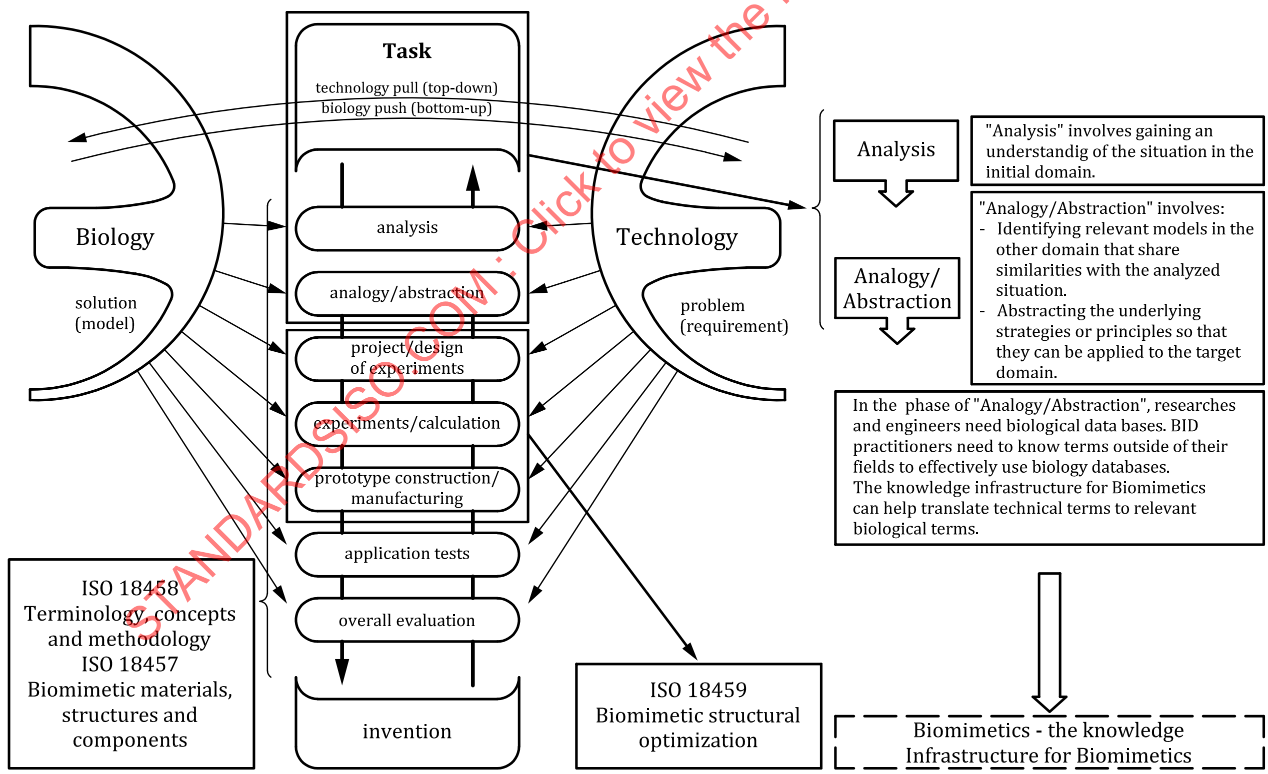

Figure 1 — Simplified flow chart of a biomimetic development process (adapted from ISO 18458)

4.2 Related work in the framework of the design processes of BID

There are quite a few methods/tools for supporting innovative design based on biomimetics or bio-inspired design (BID). They are classified according to two dimensions (see Table 1). The rows are the phase of the targeted design process ("Analysis" and "Analogy/abstraction") based on Wanieck's analysis[1]. The columns are based on a qualitative assessment of the degree of guidance the tools provide practitioners searching for BID solutions (low to high).

Table 1 — Classification of existing methods/tools

	High guidance	**Low guidance**
Analysis phase	SAPPhIRE DANE Biomimetic Ontology	BioTRIZ E2B thesaurus
Analogy/abstraction phases	SAPPhIRE DANE Biomimetic Ontology OET	iSEE AskNature

Chakrabarti[2] developed the SAPPhIRE system for automated analogical search of relevant ideas based on a generic model for representing causality in natural and artificial systems. It helps develop novel, analogical ideas for solving design problems using inspiration from both natural and technological domains.

Goel's system, named DANE (Design Analogy to Nature Engine)[3][4], facilitates analogical reasoning to help practitioners find and understand biological systems relevant to the design context. Practitioners can build structured representations of biological and technical systems using the Structure-Behavior-Function (SBF) ontology to model the systems, extract relevant principles, and build a library for the BID community. The current focus is on automatically extracting the SBF models directly from biological texts[5]. The plan is to incorporate augmented intelligence such that DANE becomes a collaboration partner in the design process.

Hollermann[6] developed a biomimetic methodology and tool for supporting creativity in product innovation based on a general concept including a detailed guideline. It supports the identification of biological models through the iSEE (iterative semantic examination) process.

BioTRIZ[7][8][9] is an extension of the TRIZ methodology to better support BID. TRIZ was developed through an analysis of successful patents[10] and has shown that it can solve problems in a wide range of topics, ranging from engineering through architecture to management. BioTRIZ consists of a set of tools, rules, and techniques to help identify possible solutions in biology.

Vincent[11] is developing a Biomimetics Ontology focusing on the trade-off as a central concept to bridge the gap between biology and problem-solving in technology. The concept of the trade-off is defined using the method of the TRIZ Contradiction Matrix. The ontology can identify trade-offs, suggest biological analogues, and uncover principles for BID.

AskNature[12] is a comprehensive database of several kinds of useful BID resources. It consists of four primary types of interconnected information: (1) biological strategies, (2) inspired ideas related to BID, (3) resources for learning/teaching BID, and (4) collections of themed clusters curated by the users. Although it provides useful information for practitioners, these types of databases require constant updating as new information becomes available and rely on the practitioner to drive the search process.

The work of Nagel[13] and Cheong[14] building on research by Stone and Shu's labs[15][16] helps fill the gap between functional terms used in engineering and biology. They employ the functional basis[17] which is widely accepted as a standardized representation of engineering product functionality in USA. They built the Engineering-to-Biology (E2B) thesaurus[18] for translating engineering function and flow terms into meaningful biological functional terms to help address the terminology issues engineers face when working between the two domains, and assist in problem definition, inspiration searching, biological functional modelling, and analogy formulation. Their work is different from OET in two respects. Their thesaurus only deals with function/flow terms, whereas OET covers organisms, features, and living environments, as well as functions. Moreover, they mainly provide biological functional terms for information retrieval, while the Keyword Explorer provides candidate organisms as possible solutions based on OET's association-based inference.

OET provides practitioners with a simple way of identifying potentially relevant organisms for future research, in comparison to SAPPhIRE and DANE that are based on models, and the Biomimetic Ontology that is based on trade-offs.

4.3 Positioning of OET in the context of the BID design process

As biomimetics is a cross-disciplinary endeavour, it is crucial for all relevant disciplines to exchange their accumulated knowledge and ideas. Each discipline has developed its unique set of concepts and words that often have different meanings and usages. Without a proper translation mechanism, communication among the disciplines will be hindered.

At a high level, practitioners of biomimetics doing "technology pull" often follow four steps[1]:

1. Analysis: gain a deep understanding of the technical problem to be solved or situation to be improved, which may involve functional analysis and abstraction as well as reformulating the challenge to simplify the second step;

2. Analogy: identify relevant biological species, phenomena, or models that share similarities to the technical challenge but suggest new ideas;

3. Abstraction: examine the relationship of the biological models to various aspects of the original technology challenge to identify underlying strategies and principles which will aid in transfer of the ideas;

4. Application: find an implementable solution to the original challenge.

In the case of "biology push", the analysis step relates to the biological phenomenon or model. The analogy step involves finding technical situations that share common drivers, while the abstraction and application steps are similar to those in "technology pull."

Access to biological databases is crucial, but these databases are organized using biological terms. Therefore, translation of the technical terms into biological terms is required.

OET has been primarily developed for practitioners but could also be valuable to biologists.

5 How Keyword Explorer works

5.1 General

Keyword Explorer is an application program running on OET that explores concepts defined in OET where each concept is used as a keyword to retrieve relevant information. The exploration mechanism is association-based. See Figure 2 where rectangles denote concepts and links denote associations (relations) defined in OET. When a user inputs "antifouling", Keyword Explore traverses the concepts in OET like a person does association-based inference.

EXAMPLE "When it gets dirty, if it automatically cleans itself (*self-cleaning*), it would work for antifouling, to self-clean, *washing out* the dirt would be also effective. To do so, *covering its surface with water* would work well. Oh, it reminds me of *hydrophilic* property which in turn reminds me of *water repellence*. *Rose petals* are well-known as their *hydrophilic* property which is opposite to *water repellence*. Rose petals realize those two properties by their *double structure* of microscopic protrusions covered with a hydrophobic waxy material which is also found on *lotus leaves*. To find something *antifouling*, would be effective to investigate organisms *living in the mud*. Ummm, *earthworms* live in the mud and their surface looks clean".

In such a way, users would be able to reach rose petal, lotus leaf, earthworm, and other organisms, some of which could be useful. They can find papers about them and would be able to find more detailed information as well as experts on the related topics.

To enable such association-based inference, different types of concepts are required. Antifouling and self-cleaning are **functions** (the role played within the larger system); washing out and covering with water are **behaviours** (how a function is manifested); water repellent and hydrophilic are **properties** (inherent characteristics of the organism); rose petal, lotus leaf and earthworms are **organisms**; and living in the mud is related to **living environment**. Furthermore, self-cleaning is a sub-function of the antifouling function, while washing out and covering with water enable self-cleaning, which suggests function-decomposition plays an important role in facilitating associative inference.

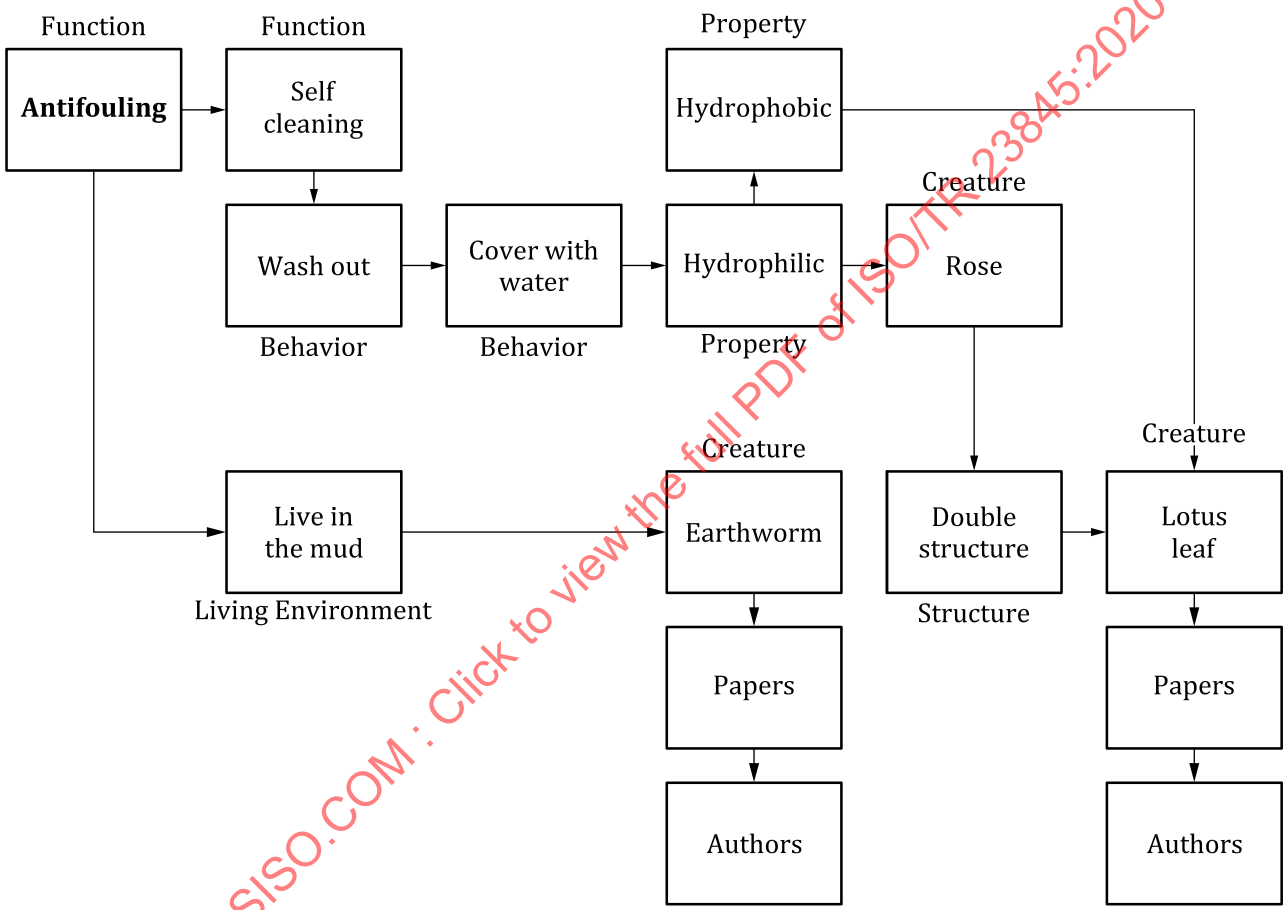

Figure 2 — Association-based inference by Keyword explorer

Ontologies play a key part in the knowledge infrastructure — Figure 3 shows how the ontologies in OET fill the gap between engineering and biology. The two vertical ovals represent conventional thesauri in the engineering and biology domains. Although each thesaurus works well in the respective domain, they would be inadequate for biomimetics which spans these two domains. Although biomimetic thesauri have been created, they have limitations as described in 6.4. Ontologies can enhance the utility of conventional thesauri by bridging conceptual gaps between engineering and biology domains.

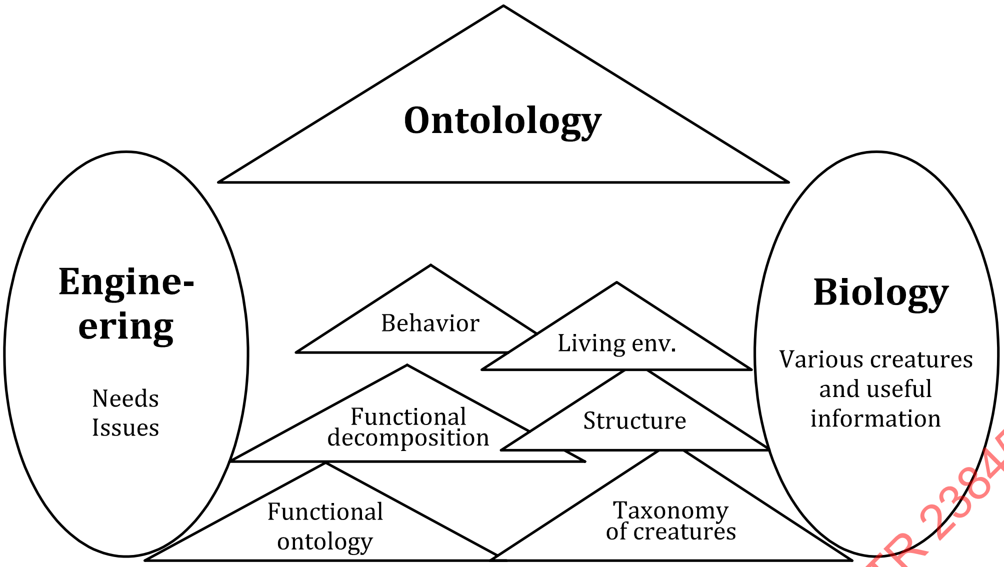

Figure 3 — Bridging the gap by ontologies

5.2 A motivating example

Imagine Jane, an engineer working in a house construction company, who is asked by her boss to invent a new eco-friendly idea for floors and walls. She finds the E2B thesaurus[18] developed based on the Functional Basis[19]. Her background is engineering, so she searches for keywords such as "easy to clean" or "stain-resistant". She tries to translate these two engineering terms into biological terms using E2B but fails because she is unfamiliar with the Functional Basis and the importance of creating a functional model that would allow her to access the right engineering terms in E2B. As an alternative, Jane could use the following two-step process.

The first step: Jane needs to find appropriate keywords that best capture her intention. At first, she only knows "stain-resistant" or "easy to clean", but she might find "antifouling" through internet searches. When she types in "antifouling", biomimetics databases will return relevant information if they contain information about biological organisms that have antifouling properties. However, not all information potentially useful for her is indexed by "antifouling" and is therefore inaccessible to her because links to this information are missing.

The second step (keyword exploration): Keyword Explorer can help Jane solve the "missing links" issue (6.4) by enabling her to explore the keyword space spanned by the OET. Keyword Explorer and OET use association-based inference to identify functions and features related to "antifouling" (at the centre of Figure 4), allowing her to find organisms such as sandfish as well as lotus and snail which are not directly indexed by "antifouling". Jane can now conduct detailed searches using a broad range of related keywords to find relevant information from biomimetics databases such as Google, Google Scholar, and AskNature, as shown in the left pane in the figure.

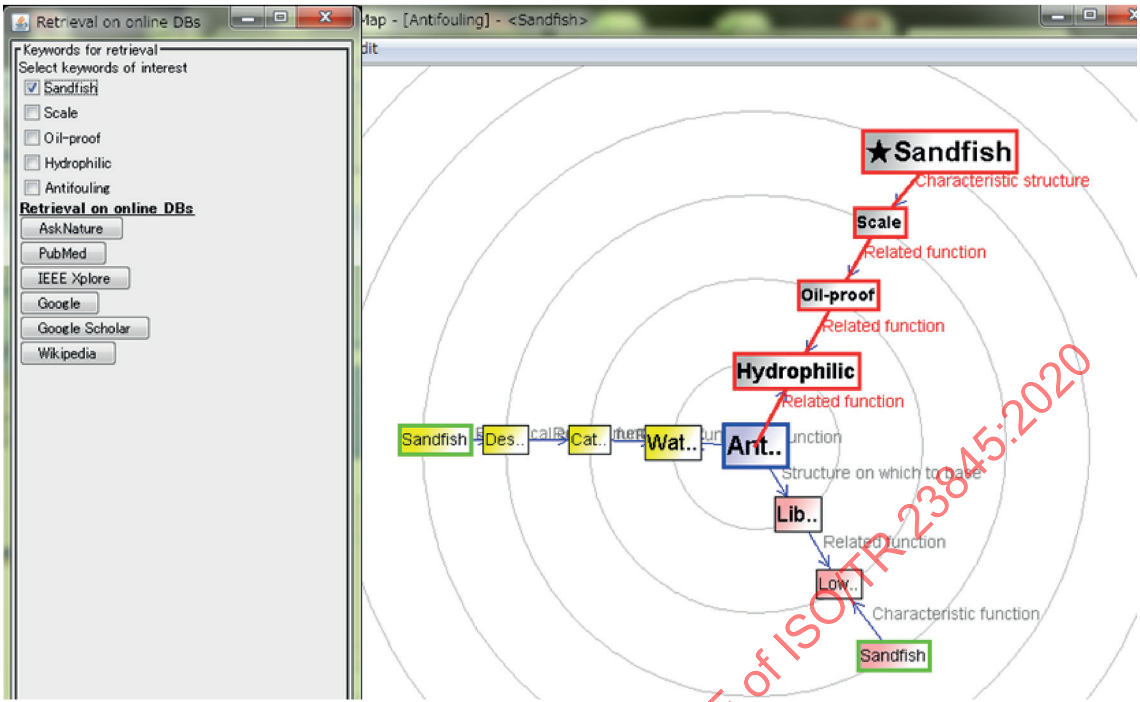

Figure 4 — Example of "antifouling" leading to sandfish via inferred keywords

The arrows in Figure 4 represent the direction in which information is linked in the ontology, rather than the progress of association-based inference.

6 Ontology-Enhanced Thesaurus

6.1 General

In this clause, the Ontology-Enhanced Thesaurus (OET) in the context of the domain of biomimetics is described. As described in 5.2, OET and "thesaurus" are well-modularized or loosely coupled so that they can work independently. A thesaurus solves terminological problems while OET solves so-called "missing link" problems described in 6.4. OET does not assume any particular thesaurus.

6.2 Characteristics of biomimetics databases

A biomimetics database is not an ordinary database which stores information about a single domain. It is an interdisciplinary database comprising not only papers on biomimetics but also all kinds of biological data, such as inventories, electron microscopy images, and experimental data.

Differences between domains cause a couple of problems including terminology differences. Practitioners doing biomimetics may not be familiar with biological terms, and hence they need substantial assistance in finding useful information about organisms that can be a source of creative ideas for developing innovative products and services. The same challenge applies to biologists who are not familiar with technical terms.

6.3 Basic design of a biomimetics database retrieval scheme

Figure 5 shows an overview of biomimetics databases with an advanced retrieval system which incorporates the above-mentioned characteristics. Various databases and other online resources can be integrated by adding metadata about them to the biomimetics ontology.

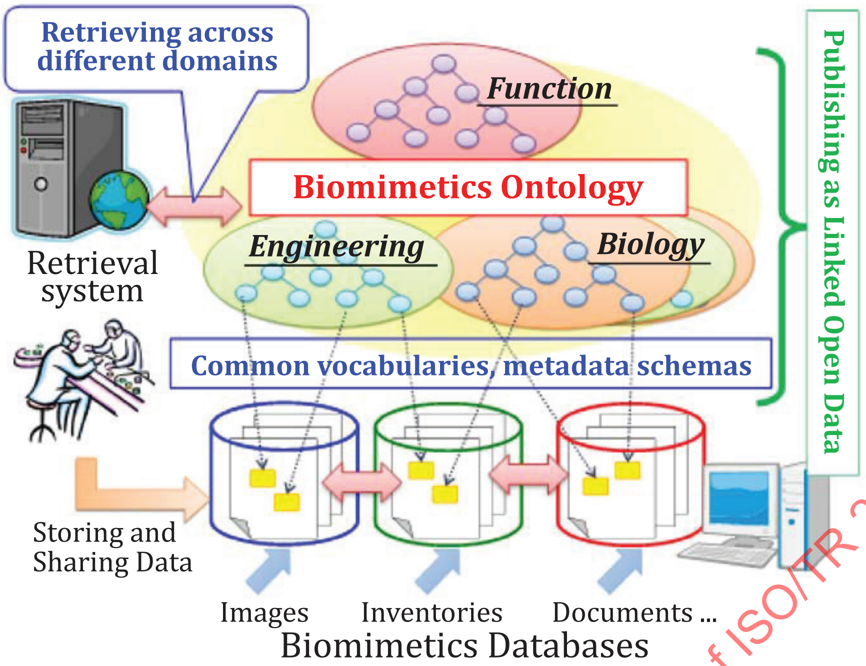

Figure 5 — Overview of the future biomimetics databases

In Figure 5 “Retrieval system” corresponds to the Keyword Explorer, while “Biomimetics Ontology” corresponds to the OET.

In general, users retrieving information from databases need to use appropriate keywords. Some retrieval systems provide users with a thesaurus, a systematic collection of terms with their relationships, to help the users with that task. A thesaurus is built using documents from the target domain and its quality is dependent heavily on breadth and quality of these documents. A biomimetic thesaurus groups together terms from the domains of engineering and biology, and therefore helps practitioners in one domain find relevant terms in the other domain. Unfortunately, biomimetics is a relatively new research topic, and hence documents about it are not mature compared with other domains. Therefore, there is no guarantee that even a thesaurus specifically created for biomimetics will include the relationships between terms used in technology and biology. OET is designed to augment the use of a thesaurus for biomimetics (see Figure 6).

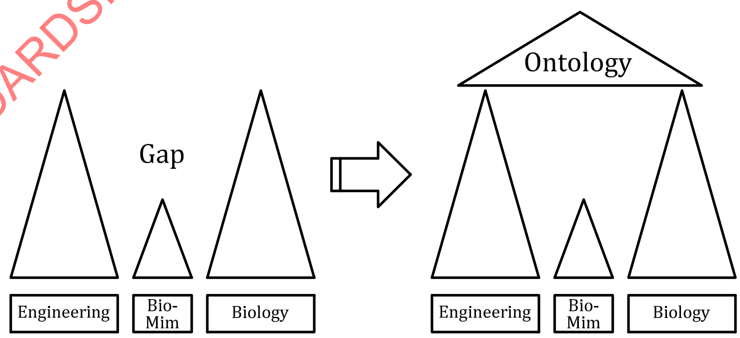

Figure 6 — Thesaurus vs. Ontology-Enhanced Thesaurus

6.4 Keyword translation and exploration

6.4.1 General

The example scenario presented in 5.2 shows how finding appropriate keywords across different domains is critical for successful searches in biomimetics databases. in biomimetics databases. If similar concepts exist in both domains, but terminology differences make linking the concepts difficult, keyword translation using an appropriate thesaurus can be useful. If concepts in both domains are associated with different terms that are not explicitly linked, keyword exploration using OET[20][21] can help fill the gap created by these "missing links". A fundamental idea behind keyword exploration is to view the ontologies in OET as a network of abstract concepts that provide a common vocabulary for associative inference. Keyword translation and exploration can be used concurrently.

6.4.2 Keyword exploration: divergent thinking

Keyword exploration for a biomimetics database aims to suggest appropriate keywords that help users find meaningful information for bioinspired innovation. The proposed system does not give users solutions to their requirements, but hints to stimulate idea creation. OET uses a generic inference engine to reduce domain specificity. Since the main purpose of OET is stimulating idea creation, keyword exploration does not require an engine based on strict reasoning (logic-based inference used in theorem proving) because that would show only well-known knowledge. What they need is help finding unexpected data/information for idea creation.

An association-based inference engine was selected to simulate so-called **divergent thinking** even though its results could include less relevant information. An ontology exploration tool developed on top of OET supports association-based inference explained in 5.2 and helps users find unexpected relationships among concepts[22]. For the same reason, the ontology in OET covers broader concepts useful for keyword exploration.

As shown in Figure B.1, OET aids divergent thinking by identifying numerous paths leading from "antifouling/antibacterial coating" via related functions to specific organisms. Four are highlighted from a range of environments: sunfish, snail, sandfish, and morpho butterfly.

6.4.3 Keyword exploration: convergent thinking

In addition to divergent thinking based on association-based inference, Keyword Explorer facilitates **convergent thinking** by allowing users to refine the candidate information. After suggesting candidate organisms to explore, it can show users a set of relevant keywords by collecting all the concepts on the paths to the user-selected organisms obtained by the associate-based inference as shown in the left pane of Figure 4. By combining appropriate concepts as keywords, users easily retrieve relevant information on several online databases (as shown in Figure B.2) to identify the most promising organisms for further investigation.

7 Ontologies in OET

7.1 General

Clause 6 describes the design philosophy of OET and the two-step keyword search on OET in the context of the envisioned biomimetics databases. This clause describes the ontologies used to build the OET prototype.

7.2 Basic design of ontologies in OET

According to a preliminary study about how practitioners use biomimetics databases and the example presented in Clause 4, the basic design of the biomimetics ontology as shown in Figure 7 was developed. OET is composed of ontologies covering function, behaviour, organisms, properties, and living environments.

7.3 Ontology of function

OET and Keyword Explorer rely on the ontology of function[23]. A key approach to compensating for “missing links” is the relationship between the target function and organisms that accomplish that function, such as the water repellence of the lotus leaf and the adhesion of the gecko’s foot. The prototype OET provides four kinds of technical functions: antifouling, low friction, adhesion, and sensing. Including sub-functions, the OET contains about 90 functional concepts. Additional details are provided in Annex A.

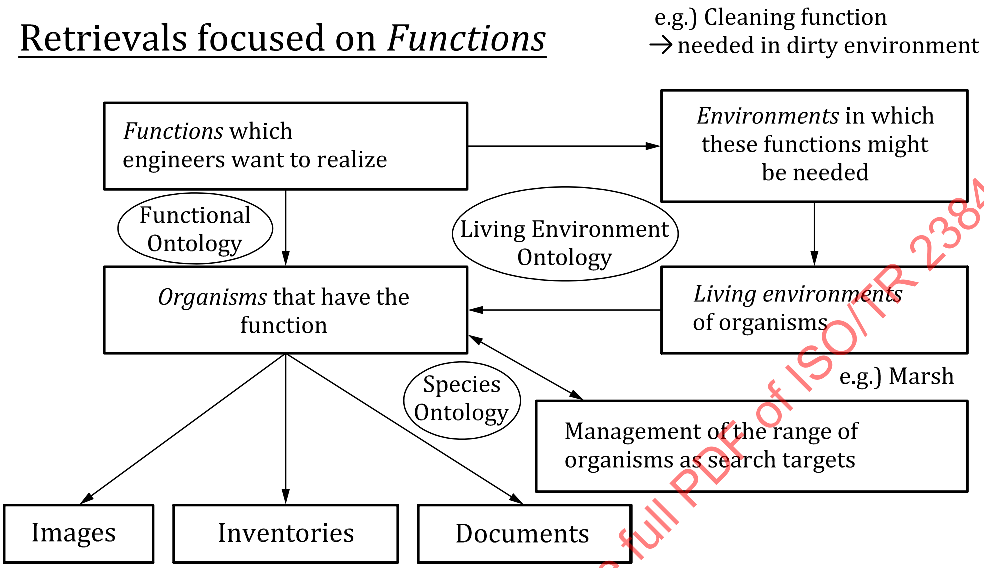

Figure 7 — Components of the biomimetics ontology and how they are used to retrieve biomimetics databases

7.4 Concepts other than function

7.4.1 Taxonomy of organisms

The target of keyword exploration is identifying candidate organisms which might have functions/structures relevant to practitioners. There are too many organisms to catalogue all of them with their property descriptions in an ontology. Therefore, a realistic strategy of starting with most of the organisms appearing in every biomimetic success story found to date was adopted. Candidates from biologists along with descriptions of their properties, functions, typical behaviours, anatomical structure, and living environments were also collected. The total number of organisms in the current OET is about 350.

7.4.2 Properties

An ontology of properties such as weight, size, temperature, and colour to describe the organisms was developed. YAMATO[24] was adopted as the upper ontology that describes general terms relevant to all domains, with features including descriptions of quality and quantity, representations, objects, processes, and events.

7.4.3 Living environments

The living environment influences the features and behaviour of organisms. Once a list of candidate organisms has been identified, the ontology of living environments can suggest other organisms that inhabit the environment and express a relevant function to cope with or benefit from the characteristics of the environment. The earthworm example in Clause 4 shows the utility of this approach. Each living environment is described in terms of properties which characterize its unique features, such as a desert is dry.

8 Implementation and evaluation of a prototype of Keyword Explorer

8.1 General

Keyword Explorer has been implemented on top of the prototype OET (see Figure 8) and it is ready for evaluation feedback from users.

Two versions of Keyword Explorer have been implemented. One is a light-weight demo system intended to let possible users to learn how Keyword Explorer works. The second is the prototype version which runs on the prototype OET. The fundamental functionality of these two implemented systems is essentially the same as the screen shots show in Annex B.

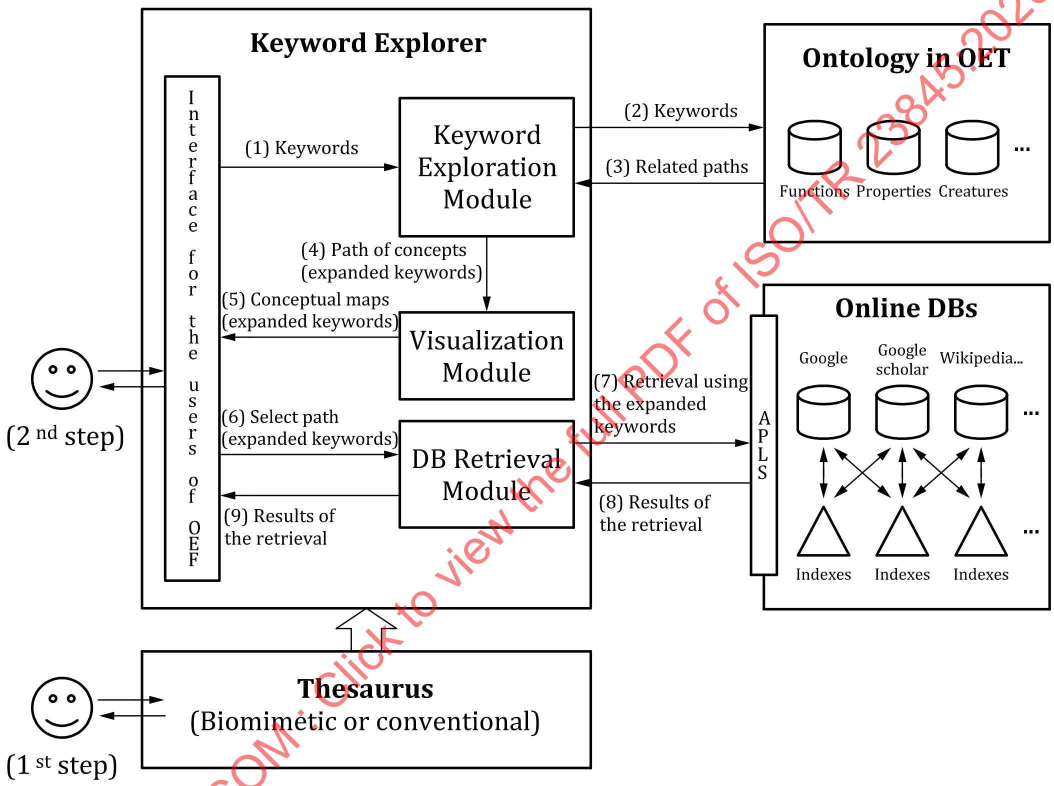

Figure 8 — Block diagram of Keyword Explorer

8.2 OET Versions

8.2.1 The demo version

The demo version is a web application which remotely accesses OET. The demo version is available at http://biomimetics.hozo.jp/OET/demo.html. The corresponding ontology can be inspected via “Browsing the Biomimetics Ontology” in http://biomimetics.hozo.jp/OET/, but it is not possible to download it. It only includes the antifouling function.

8.2.2 The prototype version

The prototype version runs as a local application using a local copy of the ontology. The major difference is the size of the ontology.

Note The ontology in OET is currently not open, but some background information along with a feedback form is available at http://biomimetics.hozo.jp/OET/. Paid users of this document can download the prototype version of OET and Keyword Explorer by contacting biomimetics@ei.sanken.osaka-u.ac.jp.

The prototype OET includes all four high level technical functions. Users can start with any of these four functions for exploration of all possible paths to candidate organisms in the search space spanning about 350 species with their properties, structures, behaviours and functions together with function decompositions of important functions

8.3 Preliminary evaluation experiment

A preliminary experiment has been performed in Japan. 20 companies belonging to a Japanese Special Interest Group on Biomimetics were asked to evaluate the utility of Keyword Explorer. Most of the members of the SIG are beginners of biomimetics/BID and are looking for new research targets. After a brief introduction and a demo of the Keyword Explorer, they were given two weeks for trial use and asked to complete a questionnaire. There were 14 responses.

The results were encouraging. As the summary of the answers in Table 2 shows, five of them answered "very promising" and six "promising" to the question "Do you think this tool can help you find useful hints for innovative design of materials/devices?" The remaining three were "neutral". In addition, all answered "yes" to the question "Do you want to use this tool after revision and enhancement?" Although some room for future improvement was suggested by some of the users, most of them were satisfied with the current functions of the prototype. Two among 14 said they were almost ready to write a new proposal of future development plan thanks to the useful information they got by this trial use.

Table 2 — Summary of responses from pilot

How many known examples did you find?		Did you find useful keywords?		Did you find some useful information through DB search?		How do you evaluate the number of keywords?	How do you evaluate the functions for managing interface?		How do you evaluate the functions for managing quantities of keywords?		Do you think this tool can help you find useful hints for innovative design of materials/devices?		Do you want to use this tool after revision and enhancement?
		I found some	4	I found some	4	many but acceptable	good	4			Promising	4	yes
Enough	4	I found many	5	I found many	5	many but acceptable	super	5	super	5	neutral	3	yes
so so	3	I found some	4	not really	2	many but acceptable	good	4	could be improved	2	very promising	5	yes
so so	3	so so	3	so so	3	too many	could be improved	2	moderate	3	neutral	3	yes
Enough	4	so so	3	I found some	4	many but acceptable	could be improved	2	good	4	very promising	5	yes
Fewer than expected	2	so so	3	so so	3	too many	could be improved	2	could be improved	2	neutral	3	yes
Enough	4	I found some	4	I found some	4	too many	good	4	good	4	Promising	4	yes
Fewer than expected	2	not really	2	not really	2	many but acceptable	could be improved	2	could be improved	2	Promising	4	yes
Enough	4	I found some	4	I found some	4	many but acceptable	good	4	good	4	very promising	5	yes

Table 2 *(continued)*

How many known examples did you find?		Did you find useful keywords?		Did you find some useful information through DB search?		How do you evaluate the number of keywords?	How do you evaluate the functions for managing interface?		How do you evaluate the functions for managing quantities of keywords?		Do you think this tool can help you find useful hints for innovative design of materials/devices?		Do you want to use this tool after revision and enhancement?
Enough	4	I found some	4	so so	3	many but acceptable	good	4	good	4	Promising	4	yes
Enough	4	I found some	4	I found some	4	just the right number	good	4	moderate	3	very promising	5	yes
Enough	4	I found many	5	I found many	5	just the right number	good	4	super	5	very promising	5	yes
Enough	4	I found some	4	I found some	4	just the right number	good	4	good	4	Promising	4	yes
Enough	4	I found some	4	I found some	4	many but acceptable	moderate	3	moderate	3	Promising	4	yes
	3,538 5		3,785 7		3,642 9			3,428 6		3,461 5 4		4,142 9	

Annex A
(informative)

Ontology of function

A.1 General

The OET ontologies help bridge the gap between technology and biology by identifying appropriate keywords for finding relevant cross-domain information. Function is at the heart of any artefact: designers produce artefacts mainly to realize required functions. A functional ontology based on abstract concepts increases its applicability. Functional decomposition which breaks a function into sub-functions is also needed.

A.2 Functional ontology[23]

The concept of function should be defined independently of the function bearer and its realization method. It originally comes from the user requirements which are object- and behaviour-independent, since users are interested in whether the solution satisfies their requirements, rather than how the solution works. Another justification is reusability of functional knowledge. Defining a function based on its bearer or realization method limits its reusability and transferability to different domains.

A framework which provides a consistent viewpoint to guide the functional modelling of artefacts as well as abstract concepts allowing sharing of functional knowledge is needed. The functional ontology has been developed to meet these requirements.

Figure A.1 shows a hierarchy of functional knowledge built on top of fundamental ontologies. Knowledge in a higher layer is described in terms of the fundamental concepts in a lower layer. The top-level ontology defines basic concepts such as time, state, and process. The extended device ontology provides a common viewpoint which supports consistent interpretation of artefacts. These two ontologies provide a foundation on which we can build consistent knowledge in upper layers.

The functional concept ontology describes what the function is going to achieve. Their definitions are very general and usable in a wide range of domains.

The ways of function achievement ontology contains knowledge about how (in what way) a function is achieved, organized in an is-a hierarchy. The is-a hierarchy is designed to identify the inherent property of each way to make it sharable and applicable across domains. One of the key issues in knowledge organization is clear and consistent differentiation of is-a relation from other relations such as part-of, and is-achieved-by, keeping what is the inherent property of the target in mind.

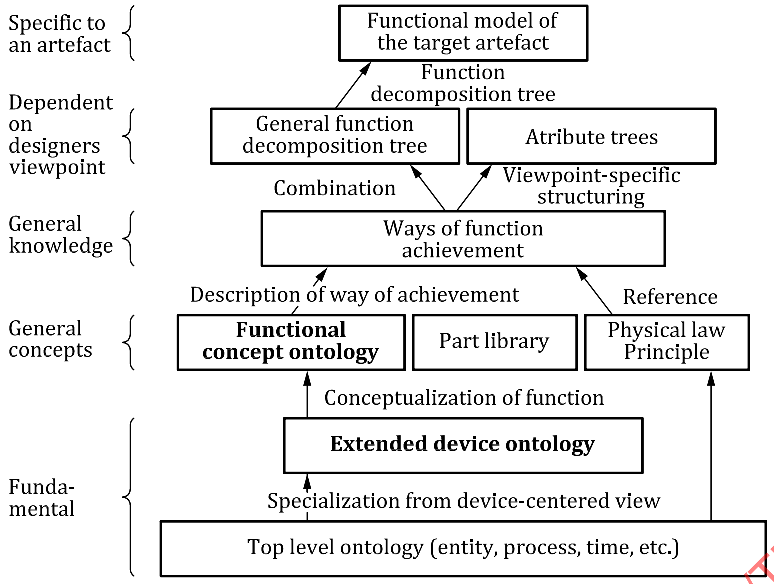

Figure A.1 — Hierarchy of functional ontology

A.3 Function decomposition[25]

The above ontologies systematize functional knowledge by clearly distinguishing between what to achieve (functional concept) and how to achieve it (function achievement way). For example, the function of a welding machine is to weld, but to weld is a composite concept of to join (what to achieve) and the method of fusion (how to achieve). The separation between these two concepts gives us a generic functional concept, to join, which is applicable to many target devices in other domains.

Any function can be decomposed into sub-functions via the notion of the function achievement way. A function can have multiple ways of realization. For example, to join two sheets of metal, the function to join is decomposed into (a) put them together, (b) melt them and (c) cool them if the welding (fusion) way is chosen, or into (a) glue each, (b) put them together, and (c) dry them if the gluing way is chosen (see Figure A.2).

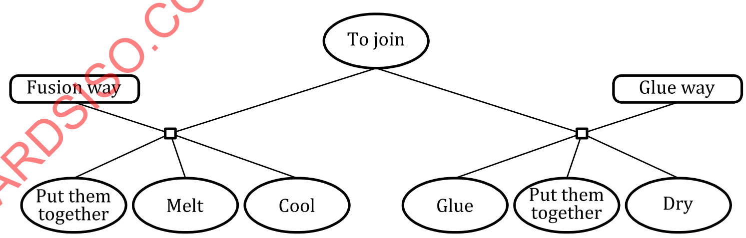

Figure A.2 — Function decomposition via function achievement ways

A.4 Core of functional ontology

Together with function decomposition, the functional concept ontology is the core of the biomimetics ontology. Functional concepts play a key role in generalizing functional terms used in daily practice. For example, the functional term to join plays a core role in conventional functions such as to weld, to glue, to fix, to staple, and to combine. Association-based inference can jump between to staple and to glue via to join, which enhances the utility of association to provide novel ways of realizing the target function. All possible functional terms used in technical domains should be stored and represented in terms of functional concept ontology together with a few typical decompositions into sub-functions via

