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Function-based, biologically inspired concept generation

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Abstract

The natural world provides numerous cases for inspiration in engineering design. Biological organisms, phenomena, and strategies, which we refer to as biological systems, provide a rich set of analogies. These systems provide insight into sustainable and adaptable design and offer engineers billions of years of valuable experience, which can be used to inspire engineering innovation. This research presents a general method for functionally representing biological systems through systematic design techniques, leading to the conceptualization of biologically inspired engineering designs. Functional representation and abstraction techniques are used to translate biological systems into an engineering context. The goal is to make the biological information accessible to engineering designers who possess varying levels of biological knowledge but have a common understanding of engineering design. Creative or novel engineering designs may then be discovered through connections made between biology and engineering. To assist with making connections between the two domains concept generation techniques that use biological information, engineering knowledge, and automatic concept generation software are employed. Two concept generation approaches are presented that use a biological model to discover corresponding engineering components that mimic the biological system and use a repository of engineering and biological information to discover which biological components inspire functional solutions to fulfill engineering requirements. Discussion includes general guidelines for modeling biological systems at varying levels of fidelity, advantages, limitations, and applications of this research. The modeling methodology and the first approach for concept generation are illustrated by a continuous example of lichen.

Keywords: Biologically Inspired; Concept Generation; Engineering Design; Function-Based Design

1. INTRODUCTION

Observation of nature has influenced the many disciplines of engineering. In recent years, plants and insects have significantly impacted engineering designs (Brebbia et al., 2002; Brebbia & Collins, 2004; Bar-Cohen, 2006*b*; Brebbia, 2006). Biological systems offer exemplary methods such as flight, imaging, sensing, adaptation, and locomotion. Engineers have learned and created novel technologies from these. The field of research into biologically inspired design, also termed biomimicry, has had many successes. For example, biomimetic robots mimic the look and functionality of an insect and, on a larger scale, achieve feats that typical robots could not. These technologies have changed the expectations of all robotic systems. The same can be said for unmanned air vehicles that copy the articulated wings of insects (Agrawal, 2007) and birds or the motion detection systems modeled after the compound vision systems of many insects (Van der Spiegel & Nishimura, 2003).

With abstraction, designers can analyze a biological system in a manner similar to an engineered system. Abstractions are critical because they allow a designer to draw parallels or make connections between domains. For example, when Koryo Miura observed that plant leaves unfold in two directions at once, Miura designed a novel folding technique (*Miura-ori*) for erecting solar panel arrays in space that requires little storage room and provides maximized surface area (Forbes, 2006). Miura-ori has also been applied to maps and Japanese drink cans, resulting in maps that are easier to collapse and cans that are stronger but use 30% less material.

Abstraction plays a major role in the early stages of engineering design and is a valuable tool during the conceptual design phase (Voland, 2004). Abstractions allow one to capture the essence of a product, process, or component within a succinct phrase, diagram, image, or domain-independent terms. Finding an appropriate abstraction is a fundamental hurdle to the use of biology as a reliable source of inspiration

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in engineering design. This research proposes using functional modeling to abstract biological systems in a repeatable and systematic manner that can be paired with existing function-based, engineering design tools. Functional modeling is often considered a fundamental step in the engineering design process (Miles, 1961; Dieter, 1991; Cutherell, 1996; Otto & Wood, 2001; Ulrich & Eppinger, 2004; Pahl et al., 2007; Erden et al., 2008; Ullman, 2009). Functional models allow a design problem to be quickly abstracted from customer needs and design requirements without requiring the design team to consider potential components, solution principles, or potential feasibility. This research is based on the functional modeling method defined in Stone and Wood (2000) and the functional basis lexicon defined by Hirtz et al. (2002). The functional basis lexicon provides the terminology to define all functions and flows required by engineered systems. Functions represent the transformation (verb) of flows (noun) of material, signal, or energy that are required by an engineered system. Functional modeling of biological systems allows biological systems to be translated into an engineering context. The information is then accessible to engineering designers who possess varying levels of biological knowledge but who possess a common understanding of engineering design methods. The advantage of modeling the flow transformations within a biological system with the functional basis is that the biological information is now an abstraction of its true form. These abstractions can facilitate the creation of connections such as analogies or metaphors that lead to creative leaps.

Creativity in engineering design is considered to have two distinct aspects: novelty and usefulness. Thompson and Lordan (1999) explain the dichotomy of creativity as "[N]ovelty may take the form of something completely new or it may be a combination of existing ideas or products. For something to be creative it must satisfy a need, it must serve a purpose and it must make a positive contribution." According to Cross (1996), the generation of satisfactory or unsatisfactory creative thoughts can be described with four generalized models: analogy, combination, first principles, and emergence. This research relies heavily on the designer's ability to identify connections between the biological and engineering domains through analogies (Gick & Holyoak, 1980; Gentner, 1983, 1988; Hofstadter, 1995; Bhatta & Goel, 1997; Goel, 1997; Mak & Shu, 2004; Linsey et al., 2008; Tsujimoto et al., 2008), first principles (McAdams & Wood, 2000; Balazs & Brown, 2001; Otto & Wood, 2001; Pahl et al., 2007), and metaphors (Casakin, 2006, 2007; Hey et al., 2008). Combination and emergence are also present when developing engineering designs; however, these creativity models are less prevalent in biologically inspired design. In addition to creativity research, there is a vast amount of literature describing engineering solutions where inspiration is derived from nature. Solutions are often novel and innovative, but generally, the inspiration happens by chance or through dedicated study.

With biologically inspired, or biomimetic, design emerging as its own field, engineering design research has begun to investigate methods and techniques to systematically transfer biological knowledge to the engineering domain. The main goal of these research efforts is to create methods, knowledge, and tools to facilitate biomimetic design. Biomimetic design "offers enormous potential for inspiring new capabilities for exciting future technologies" (Bar-Cohen, 2006*a*) and encourages engineering innovation (Lindemann & Gramann, 2004; Bar-Cohen, 2006*a*). Prominent research in biologically inspired design theory has led to focused investigation of and searching for inspiration facilitators, representation methods, information transfer methods, and concept generation techniques.

Focused searching for biological inspiration has been achieved through keyword searches of a biological corpus and software that interacts with a prepopulated database. Chiu and Shu (2007*a*, 2007*b*; Cheong et al., 2008) have developed a method for identifying relevant biological analogies by searching a biological corpus using functional keywords. The engineering domain keywords are expanded using WordNet to create a set of natural-language keywords to yield better search results. Stemming from this approach, Stroble et al. (2009) developed an algorithm to search a biological corpus first by function and then by flow. The algorithm begins with functional basis functions, but has been modified to use the function terms from the biological domain (Nagel et al., 2010).

Representation of biological systems for engineering design has taken many avenues. Chakrabarti et al. (2005) developed a software package entitled IDEA-INSPIRE that uses a database of natural and complex artificial mechanical systems categorized by a verb–noun–adjective set that captures the principle of the system (Sarkar et al., 2008). Each database entry is further classified under seven behavioral constructs. These comprise the SAPPhiRE model of causality (Srinivasan & Chakrabarti, 2009*a*, 2009*b*). Vincent and Mann (2002) used the Theory of Inventive Problem Solving (TRIZ) to abstract and categorize biological systems by the generalized engineering problems that can be solved by biology. The result was a BioTRIZ matrix that can be used simultaneously with the standard TRIZ matrix. Wilson and Rosen (2007) explored reverse engineering of biological systems for knowledge transfer. Their method results in a behavioral model and truth table depicting system functionality. Vattam et al. (2008) investigated the use of compound analogical design models to convey function, subfunction, adaptation, and analogous solution information. The compound analogy is derived from a combination of biological systems that solve the same design problem. Nagel et al. (2008) explored how to apply functional modeling with the functional basis to biological systems to discover analogous engineered systems; however, only engineered designs with more obvious biological counterparts were considered. This paper was merely an exploration on the feasibility of modeling biological organisms with functional models, and as such, it stops short of providing a methodology or approach that may be used for repeatable functional model generation. This work, however, sparked additional efforts in researching functional modeling for biologically inspired design (Shu et al., 2007; Vakili & Shu, 2007; Stroble et al., 2008). Some of the resultant models were entered into a design repository for archival and for use with existing automated concept generation techniques.

Conveying biological information in an engineering context has lead to methods of aesthetic design, material design, and determination of biologically meaningful terms. Wen et al. (2008) developed the product design from nature method that assists designers with inspiration based on biological geometric features. Vincent (2004) performed extensive research in the area of biologically inspired materials and identified the major categories of natural materials and explains how engineers can potentially benefit from each. Cheong et al. (2008) worked to provide designers with biologically meaningful words that correspond to the functional basis functions based on semantic relationships. Synonyms, troponyms, and hypernyms of functions were identified.

Concept generation techniques for biologically inspired design include diagrammatic and textual descriptions of biological organisms, strategies, or phenomena. The work of Chakrabarti et al. (2005) and Vattam et al. (2008) use images and models to develop concepts (Sarkar et al., 2008). Vincent uses the engineering contradictions of TRIZ to develop concepts. Helms et al. (2009) developed two processes for biologically inspired design that involve defining the biological solution, extraction of the biological principle, and application of the biological principle. Both diagrammatic and textual descriptions are used in the design processes. Mak and Shu (2008) studied the use of biological phenomena descriptions for idea generation. Participants were provided with support for analogical mapping and a variety of concepts were developed.

This research contributes by formulating connections between biological information and engineering systems to drive an innovative design process. This design process requires that, first, functional modeling of biological systems be formalized. Systematic design techniques may then be used based on the functional models to enable concept generation inspired by biological systems, organisms, phenomena, and strategies. Overall, this research aims to eliminate the element of chance, facilitate discovery of creative concepts, and reduce the time and effort required for biologically inspired design. The format of this paper is as follows. Section 2 discusses modeling of biological systems. Section 3 presents two approaches for concept generation that use functional models, biological information, stored engineering knowledge, automatic concept generation, and connection making. Section 4 summarizes how all of the pieces fit together within a larger engineering design context and provides a comparison with other biology-based concept generation approaches. Section 5 concludes the paper and offers future work.

2. MODELING BIOLOGY

Representing the world in terms of its function (i.e., what the world does) as opposed to its form (i.e., what comprises the world) is commonly used to abstract problems in engineering design. Functional representation enables an understanding of customer needs during conceptual design while decreasing the tendency of designers to fixate on a particular physical solution. When viewed functionally, biological systems operate in much the same way as engineered systems (French, 1994). Each part or piece in a biological system has intended functionality. Function therefore provides a convenient link to connect natural and engineering domains. Functional representation of biological systems has the potential to provide several advantages for engineering design including the following:

- systematic approach for establishing and representing functionality;
- functionality, morphology, or strategy captured at multiple levels of fidelity;
- identification of characteristics that can be mimicked by engineering means;
- creativity in concept generation; and
- archival and transmittal of information.

Functional modeling is a useful tool for capturing the essence of an engineered product, process, or component through diagrammatical means. Physically decomposing a product, process or component for redesign or curiosity, and analyzing the interactions is a common method for creating a functional model. This method is popular because the scope or boundaries of the functional model are well defined by the physical pieces and/or modularity of those pieces. A functional model can also be used in the development of a new product, and as such, the model describes the desired product functionally within the bounds of the customer needs and constraints. However, modeling biological systems is not as straightforward as modeling engineered systems. To achieve a similar well-defined scope for a biological system we propose the use of biological categories and scales during modeling. The following subsections explain the process of mapping biological terms to the engineering domain, the selection of appropriate categories, and scales for modeling, and the methodology to generate a functional model.

2.1. Mapping biology to function

Representing biological functionality using the lexicon of the functional basis allows biological solutions to be stored in an engineering design repository and used for concept generation. These biological solutions can then be recalled and adapted to engineered systems. However, modeling biological systems is not a trivial task. One cannot easily take apart a biological system, examine the parts, and associate function as one might an engineered system, nor are there customer needs to guide the designer. Rather, the designer must rely on biological literature or biologists for detailed information about the biological system in question. During the initial modeling steps, as described later in Section 3.4, a reference source should be identified to glean basic information about the biological system that offers inspiration. Biological terminology, however, could pose difficulty in learning about the biological system. An engineering-to-biology thesaurus (Nagel et al., 2010) that maps biological terms to the functional basis was employed to assist with terminological differences and to facilitate biological functional modeling. This thesaurus is a tool that associates terminology between the two domains for the identification of synonyms.

The approach to modeling biology with the functional basis presented in this paper aims to accurately reflect the material, signal, or energy flows carrying out biological system functions. Note that *biological* is included the functional basis as a secondary-level energy flow; however, this approach discourages its use. Because engineered systems lack a *biological energy*, its use as the primary energy source in a biological system would limit or even inhibit a designer from making connections between the engineering and biology domains. To encourage connections, care should be taken to select material, energy, and signal flows that would commonly appear in an engineered system. The engineering-to-biology thesaurus may be used to find appropriate function and flows terms.

Consider lichen as a biological system to illustrate the mapping of biological terminology to the functional basis. Lichen is a symbiotic organism comprising a fungus (mycobiont) and an organism capable of producing food by photosynthesis (photobiont), typically a green algae or cyanobacterium (Ahmadjian, 1993; Brodo et al., 2001; Nash, 2008). Lichens grow in almost every climate and thrive where other organisms refuse to live, such as harsh climates or in areas of limited resources, which can include bare rock, desert sand, cleared soil, dead wood, animal bones, rusty metal, and living bark (Brodo et al., 2001). A lichen can survive such conditions because of the symbiosis in which the mycoboint physically protects the photobiont from predators and too much sunlight in return for carbohydrates to live (Ahmadjian, 1993; Brodo et al., 2001; Nash, 2008; B. McCune, personal communication, February 22, 2010). In addition to sunlight, lichen also need water and nutrients to sustain life and perform photosynthesis. Nutrients consist of elemental chemicals (e.g., oxygen, carbon, nitrogen) and minerals that are derived from the atmosphere, taken up from a substrate, and transported to lichen by rain water or droplets from the surrounding environment. The photobiont communicates with the mycobiont to receive more or less sunlight, water, and nutrients to fuel the photosynthesis, whereas the mycobiont communicates to the photobiont when more carbohydrates need to be produced (B. McCune, personal communication, February 22, 2010). For lichen to form, mycobiont and photobiont must encounter each other on a stable surface. Once the mycobiont secures itself around the photobiont, fully enclosing the photobiont, a surface is no longer required. Lichens can take on different appearances based on their growth form. The major difference between the growth forms is the location of the cortex and whether it is centralized or spread out (Nash, 2008). Functionally speaking, all growth forms of the lichen are similar in principle with differing morphology.

A design question must be posed to scope a functional model of an engineered system. The same holds true for biological systems. A design question provides the starting point from which to begin researching the biological system of interest past basic information. Consider the following design question for the lichen. *How do the mycobiont (fungus) and photobiont (photosynthetic organism) interact to survive as the symbiotic organism, lichen?* Table 1 captures the biological flows that have been identified for lichen and the functional basis translations that are salient to understanding the lichen symbiosis and aid in answering the posed design question.

2.2. Defining mimicry categories

Mimicking a biological system for the creation of biologically inspired technology has occurred through several mechanisms. This research investigates biologically inspired design through functional modeling. The fundamental difficulty in modeling biology occurs with comprehending the multiple viewpoints of a biological system. Understanding how biological knowledge is interrelated, yet categorizable, offers a designer insight on how to manage the nonengineering domain information such that it can best aid the design process. Researchers discovered (Raven & Johnson, 2002; Campbell & Reece, 2003) that biological organisms have three outlets for interacting with a changing environment: physiology, morphology, and behavior. A biological organism will adapt new functionality (physiology) or structure (morphology), or learn a new behavior to obey the instinctual actions of *protect, reproduce*, and *sustain*. Additionally, the authors noticed similar behavior (e.g., change shape, expose pores, drop off-

Table 1. *Relationship between lichen flows and the functional basis*

Biological Information	Functional Basis Flows
Fungus (*mycobiont*)	Liquid–solid mixture material
Green algae or cyanobacterium (*photobiont*)	Liquid–solid mixture material
Photobiont uses *sunlight* to perform photosynthesis	Electromagnetic energy
Nutrients	Solid material
Water	Liquid material
Symbiosis	Liquid–solid mixture material
Photosynthesis creates *carbohydrate sugars*	Chemical energy
Photobiont *communicates* with mycobiont to receive more or less sunlight, nutrients, and water	Control signal
Predators	Material
Mycobiont creates *poisonous coating* to prevent predators from eating lichen	Solid–solid mixture material

Note: The lichen flow information is according to Ahmadjian (1993), Brodo et al. (2001), and Nash (2008), and the functional basis information is according to Hirtz et al. (2002).

shoot) across multiple biological ranks (i.e., kingdom, phylum, class, order, family, genus, species) that were initiated and carried out for dissimilar reasons; these are termed strategies. Thus, four biological categories are proposed and are defined as the following (Matrin & Hine, 2000; Raven & Johnson, 2002; Campbell & Reece, 2003; Henderson & Lawrence, 2005):

- Physiology: the vital functions and activities of organisms, as opposed to their structure
- Morphology: the form and structure of an organism, and the associations among the structures of an organism
- Behavior: the sum of the responses of an organism to internal or external stimuli
- Strategy: generic behavior that is exhibited among multiple biological ranks to achieve different goals

Note that behavior was separated from strategy to allow insight into specific, within biological rank, actions a biological system takes that may or may not be part of the overall strategy. Strategy was kept as a separate term to alert the designer of repeating behaviors that span multiple biological systems but result in different outcomes.

When creating an abstraction to represent a biological system, considering questions that each of these categories answers can help to clarify and direct how the model is created. For example, asking a question about behavior and/or strategy is exploring the question of *why*. Asking a question about physiology explores the question of *what*, and asking a question about morphology explores the question of *how*. Mimicry categories can aid the designer with defining a boundary when developing a functional model for use with design activities, but can also stimulate the designer to consider the biological system from different viewpoints. Without customer needs and constraints to guide the initial design process it is easy to be overwhelmed by the quantity and unfamiliarity of the available biological information. Unless the biological system is well known and easily understood, it is easy to overstep (or understep) the modeling scope with the biological functional model. Therefore, utilization of biological category is the first step to assist with putting the information into perspective. The designer must take cues from literature or biologists as to what information represents the category of interest. In addition to answering a design question related to the biological system (described in Section 2.1), the biological functional model must also comply with a chosen biological scale (described in Section 2.3).

Reconsider the lichen and the design question posed in Section 2.1. Understanding how the mycobiont and photobiont work in symbiosis to survive requires knowledge of the principal functionalities of the two organisms that comprise the lichen, and how they each contribute to the symbiosis. To define the biological category used during functional modeling requires investigation of physiology, morphology, behavior, and strategy of the biological system. Realizing that the mycobiont and photobiont are both organisms initially points to the *physiology* category. However, because survival is posed in the design question, it could also be argued that this includes the *behavior* category. To further narrow in on which category is of interest, it is necessary to return to the design question. Although survival is discussed, it is in the context of interaction between the mycobiont and the photobiont. There is no discussion of possible external stimuli such as harsh climates or areas of limited resources. Further research into the symbiosis of the two organisms reveals that lichen employs resource sharing in exchange for protection. These are elements that fall within the vital functionality of the organism. Therefore, we will consider that the boundary set for the lichen functional model is the category of physiology.

2.3. Identifying biological scales

The second tool to assist with placing biological information within the right perspective is biological scale. Biological scale deals with how much detail is required for developing an adequate representation of the biological system, while adhering to the chosen biological category and posed design question. As an additional model boundary, biological scales assist with defining the level of detail required to create a functional model of a biological system. The goal is to use biological scales to assist with scoping the biological functional model for use with existing function-based, conceptual design tools. Biological computational models are used as a framework for biological scales. The biological computational models range from atomic level to population and have the following order: atomic, molecular, molecular complexes, subcellular, cellular, multicell systems, tissue, organ, multiorgan systems, organism, population, and behavior (White et al., 2009).

Although the biological scale can be viewed as a constraint on the model, it is also a creative design challenge. It is possible to derive multiple connections to engineering from a single biological system by considering more than one scale of the same biological system. This has been demonstrated by Shu et al. (2007). For example, considering the organism scale of a biological system might inspire an idea for a new and innovative consumer product, whereas considering the tissue scale of the same biological system might inspire a novel material. Advantageous starting points are the cellular, organ, and organism biological scales as they are readily defined in biological literature.

When generating a biological functional model, the biological scale is often constrained to a single scale (e.g., the model contains only elements from the organ scale). Generating models constrained by a biological scale tends to be more analogous to how engineered systems are modeled; however, functional models can represent mixed biological scales to demonstrate specific biological phenomena of interest to the designer. Just as for category, the designer must take cues from literature or biologists as to what information represents the scales of interest. It is important when developing mixed-scale biological functional models to remember that any concepts derived from the connections made between natural and engineered systems will also be of mixed scale. This concept of mixed model connections is further demonstrated by the lichen example.

Lichen physiology was demonstrated at multiple biological scales, and the answer to the posed design question can be best captured with a mixed-scale functional model. Modeling lichen at the organism scale would convey that two materials are secured together in the lexicon of the functional basis. This result, however, does not fully answer the posed design question because we do not know how the two organisms interact. Thus, we must mix the scales to include the organ scale to fully understand the interaction between the mycobiont and the photobiont. Examining lichen at the organ scale reveals that the photosynthetic organism performs photosynthesis in return for sunlight, environmental, and predator protection. Photosynthesis performed by the photobiont produces carbohydrate sugars. These carbohydrates are made available for both organisms; their consumption by the mycobiont provides for sunlight, environmental and predator protection, and their consumption by the photobiont allows the photosynthesis process to continue. The intake and transfer of sunlight, water, and nutrients by the mycobiont and its conversion to carbohydrates by the photobiont, answers half of the posed design question. The other half relates to the mycobiont. The mycobiont (fungus) forms around the photobiont offering protection from excess sunlight, harsh environmental conditions, and from predators. This filtering of light, sharing of water and nutrients, and the production of chemicals to repel predators must be added with the intake, transfer, and conversion of sunlight mentioned above to completely answer the posed question. To direct the biomimetic concept using the organ scale alone would result in a design that acts more as a component than a product, whereas the organism scale would act, at least at a high level, as a product. Looking at a more detailed scale such as the molecular scale would focus on the chemical reactions of the Calvin cycle (Campbell & Reece, 2003) occurring during photosynthesis to produce the carbohydrate sugars; this might be interesting from an analogical standpoint, but this detail is outside the scope of the posed design question. Thus, a mixed-scale model comprising *organism* (photobiont and mycobiont) and *organ* (carbohydrate production and predator deterrence) biological scales is considered for lichen.

Realizing that lichen only exists when there is a symbiosis conjures up the basic instinctual actions of sustaining and protecting life; thus, the black box model of the system is described as provision (i.e., to accumulate or provide a material or energy flow; Hirtz et al., 2002). As input flows, the mycobiont and the photobiont are both brought into the black box. These two organisms are represented as liquid–solid mixture materials because of their aqueous composition. The water, nutrients, and sunlight necessary for survival are also brought into the model; lichen is formed inside the black box. The primary flows identified in Section 2.1 include the photobiont, mycobiont, water, nutrients, and predators as materials and sunlight as the energy of the systems. This black box model is provided in Figure 1.

2.4. General biological modeling methodology

During the course of this research several functional models of biological systems were created, edited, and finalized. Based on these experiences, the following general methodology for functionally representing biological systems is presented. The motivation to functionally model biological systems stems from prior work by Nagel et al. (2008), which proved the feasibility of developing biological functional models. The methodology offers a designer direction when creating a biological functional model and provides empirical guidelines to improve model accuracy. The methodology is as follows:

1. Identify a suitable reference (e.g., biology text book) for the biological system of interest.
    a. Similar to performing a study of an engineering system, it is important to have the most current sources of information to guide the modeling process to ensure that the model represents the most current understanding of the strategy, behavior, physiology and morphology of the biological system in question.
2. Read the overview of the biological system to understand the core functionality of the system.
    a. Take notes that capture the essence of the biological system.
    b. Pay attention to categorical or scale cues in the literature (e.g., reading about dendrites cues the scale of cellular because the definition of a dendrite is "a short branched extension of a nerve cell"; Campbell & Reece, 2003).
    c. Refer to the engineering-to-biology thesaurus for guidance on how biological flows relate to flows found in engineered systems.

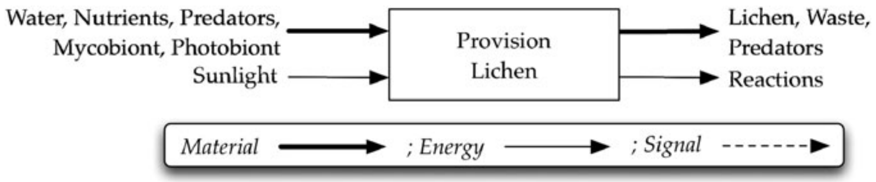

Fig. 1. A black box representation of lichen.

3. Define the design question the functional model aims to answer.
   a. This question posed about the biological system should direct the designer toward an answer, which is similar to defining an engineering problem statement that leads one toward a solution.
4. Define the category of the functional model.
   a. Use the four categories to consider the biological system from different viewpoints and determine which category best aids with answering the design question.
5. Define the desired scale of the model.
   a. Begin by modeling the black box for the biological system defining the overall functionality with the functional basis lexicon.
   b. Investigate what occurs at the desired biological scale to achieve the black box functionality (i.e., subfunctions).
   c. Read about the biological system noting the sequential and parallel events that occur to achieve the black box functionality.
6. Develop a functional model of the biological system using the functional basis modeling language within the bounds set by the design question, biological category, and biological scale.
   a. Use the engineering-to-biology thesaurus to choose the most suitable functions to accurately represent the biological system.
   b. Make sure implied functions such as transfer, transmit, and guide are added to the model between major biological events.
   c. Do not mix the function of the supporting structure with the core functionality of interest within the functional model (e.g., the stalk of a sunflower *transports* nutrients and water from the soil to the head for producing fruit, and should not be mixed with the stalk as a *support* for the sunflower).
   d. Use a software program that allows quick rearrangement of blocks to make this process quicker (e.g., FunctionCAD at http://www.designengineeringlab.org/functioncad/, OmniGraffle at http://www.omnigroup.com/products/OmniGraffle/, or Visio at http://office.microsoft.com/en-us/visio/).
7. Double check and/or validate (e.g., have a biologist review model at desired biological category and scale) the functional model against the design question and black box model.
   a. Keep in mind that familiar terms to engineers could be used in a different context in the biological system description (e.g., the term bleaching does not refer to the removal of color; with respect to vertebrate eyes, it means the retinal and the opsin eventually separate, which causes lose of photosensitivity; Campbell & Reece, 2003).

The majority of, if not all, design processes are iterative and this modeling methodology follows the same convention. As models are formalized for a biological system, iterations will rearrange and change the functions used to represent biological functionality. Functional models are an abstraction; they help to formalize and develop an understanding of a design question. Therefore, it is natural that as models are generated, the designer's understanding of the biological system will improve, and consequently, the functional model will evolve. The goal of the general biological modeling methodology presented here is to provide a guideline from which engineering designers can build a functional model to enable future biomimetic design opportunities.

Investigating the lichen functionality, the flows required, and the biological system category and scales in Sections 2.1–2.3 resulted in a well-defined scope and boundary. Continuing with the lichen example the functional model, shown in Figure 2, is decomposed from the black box model of Figure 1. The functional model, as discussed in Section 2.3, represents two biological scales. The photobiont being *secured* by the mycobiont and the *prevention* of predators represents the organism scale portion of the mixed model. The *regulation* of water, nutrients, and sunlight; *conversion* of water, nutrients, and sunlight into chemical energy; *storage* and *supply* of chemical energy; *conversion* of chemical energy into a protective coating; and *measurement* of chemical energy represent the organ scale portion of the mixed model. Functions within the striped shaded area are at the organ scale for the mycobiont and functions within the solid shaded area are at the organ scale for the photobiont. In the organ scale portion of the model sunlight is imported as electromagnetic energy. The conversion of sunlight, water and nutrients into chemical energy is fueled by previously stored chemical energy, which is supplied to both the photobiont, to power further carbohydrate production, and the mycobiont, to allow protection.

The water, nutrients, and sunlight enter the striped shaded area (Fig. 2, also labeled mycobiont organ scale) where they are regulated by communication from the photobiont. The mycobiont allows the regulated energy-rich nutrients to pass through and enter the solid shaded area (Fig. 2, also labeled photobiont organ scale) where a conversion creates carbohydrate sugars, which are modeled as chemical energy. Chemical energy (sugar) is one of the biological correspondent terms of the engineering-to-biology thesaurus for chemical energy. The photobiont stores a small portion of the carbohydrate sugars for reserve, uses a portion immediately to continue fueling the conversion process, and passes the remainder to the mycobiont. The mycobiont also creates a store of carbohydrate sugars; they are supplied as necessary for its survival. Store is used to represent the conservation of carbohydrate sugars for future consumption based on the biological corre-

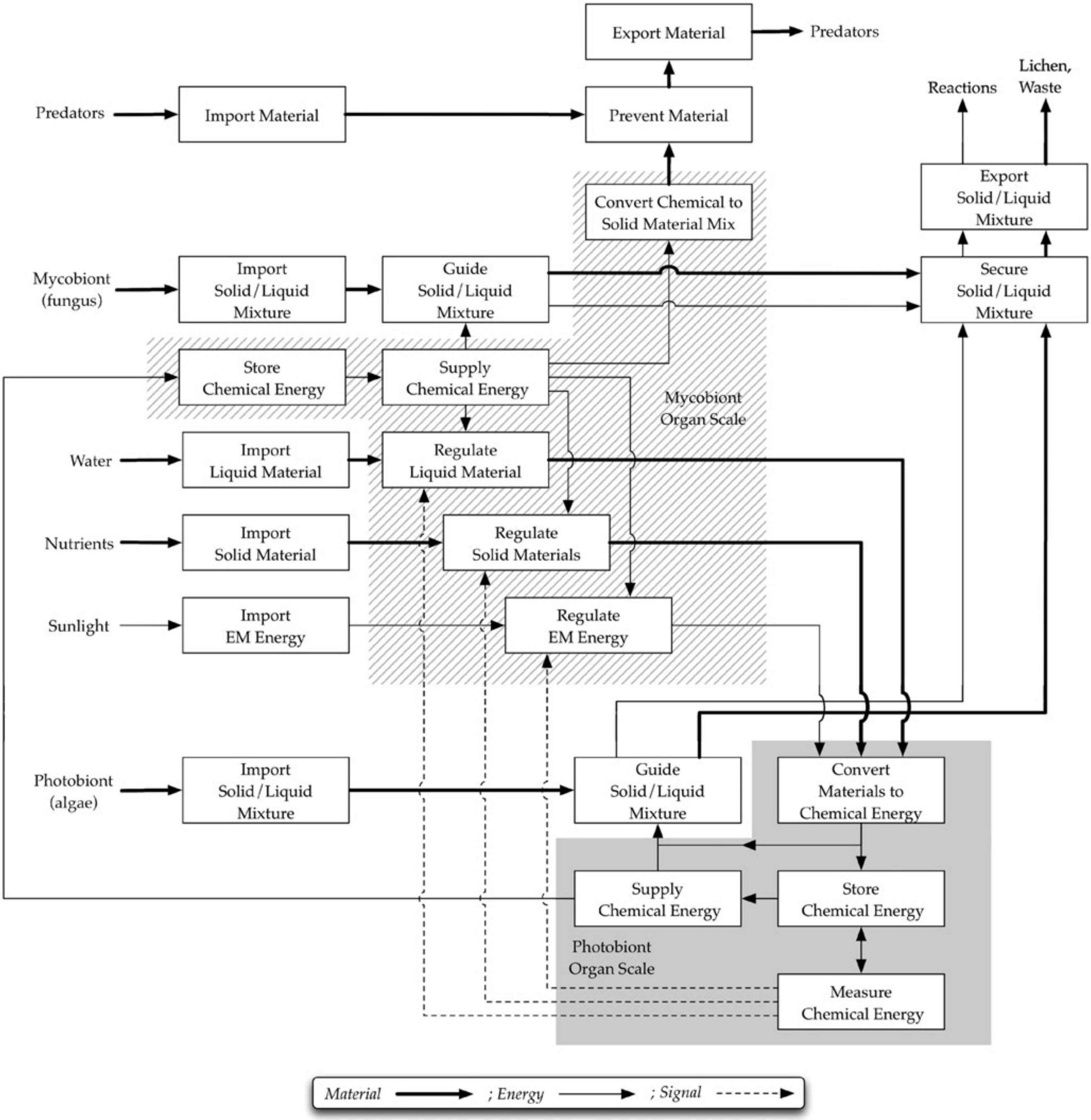

Fig. 2. The lichen functional model.

spondent term of conserve, as well as the definition of the term store: “to accumulate a flow” (Hirtz et al., 2002). Supply is used to represent the use of stored carbohydrate sugars for consumption based on the thesaurus biological correspondent term of feed, in addition to the definition of the term supply: “to provide a flow from storage” (Hirtz et al., 2002).

The model in Figure 2 also investigates the basic instinctual action of protection at a deeper level of abstraction. Included at the mycobiont organ scale is the creation of the toxins that protect the lichen from predators. The mycobiont, which is the outer organism of lichen, excretes a coating that crystallizes on its surface to repel lurking predators. This coating can give off a smell, can taste foul, and can be toxic; this is dependent on the species of lichen (Nash, 2008).

The biological functional model was validated through two discussions with a lichenologist, and comparison to existing model abstractions in biological texts and known flows. During the first meeting with the lichenologist of the Oregon State University (OSU) Plant Pathology and Botany Department, an initial lichen functional model was presented

(B. McCune, personal communication, February 22, 2010). This initial meeting consisted of the researchers and the lichenologist arriving at a common understanding of the nomenclature required to describe a biological system as an engineered system and to describe a biological system to an engineer. The lichenologist explained how our initial representation, although correct based on the initial literature review used to generate the model, fails to capture the most recent advances and understanding in the field (Nash, 2008), and that the symbiosis is a two-way arrangement where the mycobiont offers protection (both from predators and from excess sunlight) to the photobiont. Figures 1 and 2 represent the models created following the initial discussion with the lichenologist. These two models were verified and approved during the second meeting (B. McCune, personal communication, March 4, 2010). This validation further supports the suitability of the mixed scale and chosen category used to guide the generation of the functional model for answering the posed question.

3. APPROACHES FOR CONCEPT GENERATION

The following two concept generation approaches were created to enable systematic conceptual design of biologically inspired engineering solutions using existing function-based design tools and methods. Rather than task the designer with deciding when to consider biological information during concept generation, these two approaches provide guidance through the process and reduce the time and effort required. Overall, they aim to eliminate the element of chance and facilitate discovery of creative concepts. Function-based automated concept generation may be extended in two ways with the addition of biological information. The typical approach would generate a functional model based on customer needs. Automated concept generation techniques would then be used to identify potential engineering solutions for each subfunction of the model. This approach is modified by the two extensions shown in Figure 3, which can lead to biologically inspired conceptual designs. Both use functional models to focus queries of a design repository. Furthermore, both concept generation approaches encourage one to make connections, similar to the creative process of synectics (Gordon, 1961; Prince, 1967, 1970), between biological and engineered systems. Making connections is generally achieved because of prior knowledge and experience, which is similar to case-based analogical design (Kolodner et al., 1985; Goel & Chandrasekaran, 1988; Birnbaum et al., 1991; Slade, 1991; Haas et al., 1993; Maher & de Silva Garza, 1996; de Mantaras & Plaza, 1997). Prior knowledge of a broad range of engineered systems and processes is not required for concept generation; however, that knowledge provides the impetus for readily recognizing the connections between systems of two dissimilar domains. The first approach, shown as a dashed line in Figure 3, uses a functional model developed from a biological system (discussed in Section 2) to discover corresponding engineering components that mimic the functionality of the biological system. The second approach, shown as a solid line in Figure 3, uses a conceptual functional model developed from customer needs to discover which biological components currently stored in a design repository inspire functional solutions to fill engineering requirements.

3.1. Approach 1

Concept generation approach 1 is a technique for concept generation of innovative products that begins with functional models based on systems of interest, rather than deriving a product directly from customer needs. A form of this method has been used for the redesign or improvement of failed products by modeling a product originally derived from customer needs and identifying the functions that need improvement. This approach may also be used when inspiration is taken initially by a chance observation of a biological system. To meet customer expectations when following the first approach, the designer takes inspiration from another system or domain, in this case biology, to discover how the product can be improved. A designer would use this approach to explore the possibilities that other systems offer for the redesign of a product or use it as a creative exercise to make connections between biology and engineering.

To follow the first approach for concept generation, a biological system of interest must first be identified. A functional model of the biological system is then created and used to query a design repository for potential engineered solutions to each

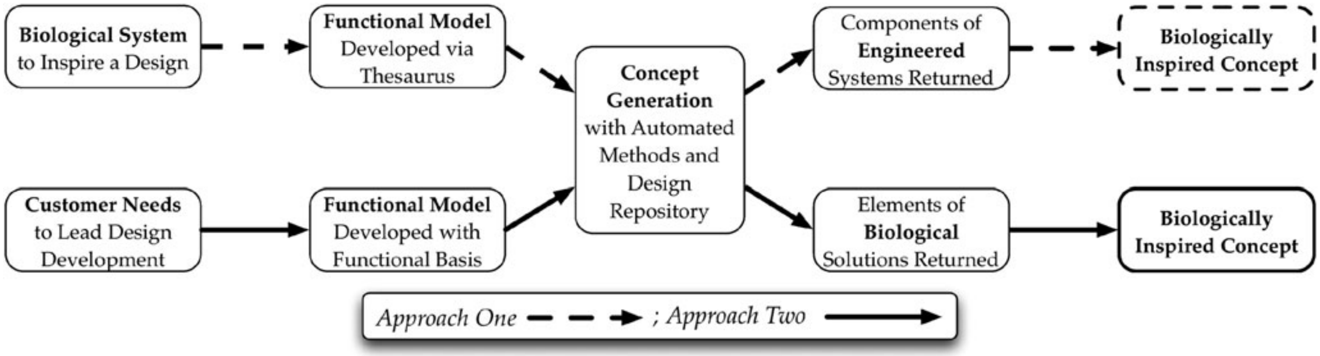

Fig. 3. A summary of the concept generation approaches.

function using an automated concept generator. The input is processed, and a set of engineering components is returned for each function–flow pair in the biological functional model. The designer then chooses from the resulting engineering component suggestions to develop a complete conceptual design that mimics the biological system. The systematic methodology of approach 1 is as follows:

1. Generate a functional model of the biological system of interest following the procedure outlined in Section 2.
2. Query a design repository for solution principles for each function–flow pair in the biological functional model.
3. Review the engineering components returned by the automated concept generator that fulfill the same functionalities as the biological system.
4. Generate concepts by mixing and matching solution principles identified through queries to a design repository.
5. Continue with the conceptual design process and/or proceed to embody and detail the design.

Consider again the lichen example. In the previous section, step 1 is completed, and the functional model of the lichen is provided as Figure 2. To follow step 2, we access the Design Repository (http://www.designengineeringlab.org/delabsite/repository.html) housed at OSU with the automated morphological matrix tool (Bohm et al., 2008) and the concept generator software, MEMIC (Bryant, McAdams, et al., 2005). The biological functional model is first created in Function-CAD (Nagel et al., 2009) software and is then exported as an adjacency matrix (a two-dimensional matrix capturing the topology of the functional model) to MEMIC (http://function2.mime.oregonstate.edu:8080/view/MEMICv2-2.zip). MEMIC returned engineering components for half of the lichen function–flow pairs; for the remaining half of the function–flow pairs, MEMIC returned an incompatibility error meaning that engineering systems were not known to solve the function–flow pairs in the same order as they occur in the biological system. To find solutions for these remaining functions the Design Repository was queried with the morphological matrix tool. The chosen engineered solutions have been substituted for each function in the functional model of the biological system and is provided in Figure 4. Components marked with an asterisk were not found directly from queries to the Design Repository. To identify these remaining components, functions were queried minus their flows using the Design Repository.

This concept generation approach is limited by the data available in the design repository being queried; when data is available, connections are easily discovered between biology and engineering as demonstrated through the lichen example. The multiple engineering solutions returned, however, may not make immediate sense. Thus, this approach requires a large amount of insight from the designer to be able to make the necessary connections leading to a feasible engineering concept. This approach, therefore, lends itself more toward innovative design problems where novel solutions tend to dominate.

To develop an engineered solution from the components shown in Figure 4, a designer must also consider the scales that were chosen for the functional model. Although the model represents the symbiosis, it also contains two separate organisms to perform the photosynthesis, coupling, and protection, which comprise the symbiosis. In the engineering component model of Figure 4, the reservoir, housing, lens, cover, and tubing are analogies drawn at the organism scale whereas the pump, valve, film, battery, and sensors components were drawn at the organ scale. When considering scale, a symbiotic product where one device contains and protects a separate second device is analogous. Then, when considering components in a similar structural relationship as lichen, the leap that is made is to an innovative solar thermal collection device. A sketch of the conceptual design is given in Figure 5. The innovative device consists of a solar panel surrounded by a reservoir. The reservoir is filled with a liquid material that acts both as a filter and as a lens directing solar energy to the panel. A pump cycles liquid from the reservoir into an exchange tank where thermal energy can be added or removed from the liquid keeping the surrounding liquid temperature optimal for the solar panel. Excess thermal energy removed from the liquid can be used to supplement a domestic hot water heating system. A battery stores electrical energy created by the solar panel; this power could be used to supplement a domestic power system but is also required to run the pumping system.

3.2. Approach 2

The second concept generation approach leading to biologically inspired solutions follows the typical method of automated concept generation outlined in Bryant, Stone, et al. (2005). The potential customer is interviewed to identify customer needs. The customer needs are translated into functionality for the product being designed. A black box model and functional model are developed and used to query a design repository for solutions to each function. In order for biological inspiration to occur using this typical method, the design repository being queried requires biological entries. Then, when the designer queries the repository, biological solutions are returned for functionality in the conceptual functional model. The designer would then have the choice to use or ignore the biological solutions for further concept generation.

Entries into the design repository can be any of the biological categories or scales previously described, and often one biological system will offer multiple functional models where each describes a different category and/or scale. Descriptions and images are provided with each artifact to assist a designer with overcoming any potential knowledge gap between biology and engineering, thus facilitating inspiration and connection making during the design process. The Design Repository housed at OSU is populated with 30 biological phenomena that can be returned with both the automated morphological matrix tool and with the MEMIC software. The systematic methodology of approach 2 is as follows:

1. Create a conceptual functional model of the desired engineering system based on mapping customer needs to flows (Otto & Wood, 2001; Ulrich & Eppinger, 2004; Pahl et al., 2007; Ullman, 2009).
2. Use an automated concept generator to query potential solutions for each function–flow pair in the conceptual functional model.
3. Review engineering and biological solutions retrieved by the automated concept generator.
4. Explore biological solutions for inspiration to functionalities (i.e., read the repository entry, look over the functional model, read more about it in a biological text).
5. Identify novel engineering solutions for functions that are inspired by biology or, if none are identified, choose alternative solutions from the automated concept generator.
6. Continue with the conceptual design process and/or proceed to detailed design.

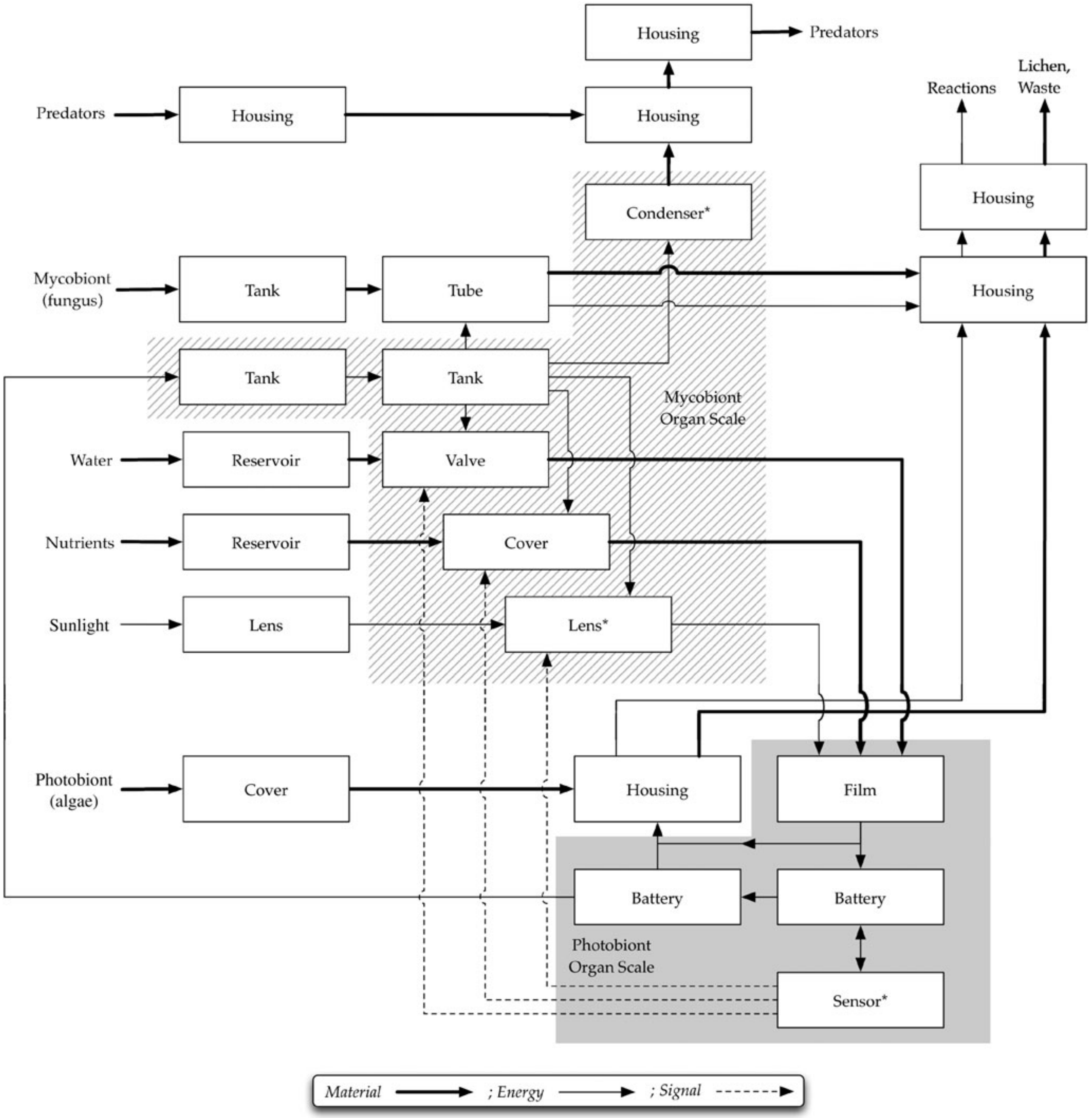

Fig. 4. The lichen model with engineering components. *Components not found directly from queries to the Design Repository.

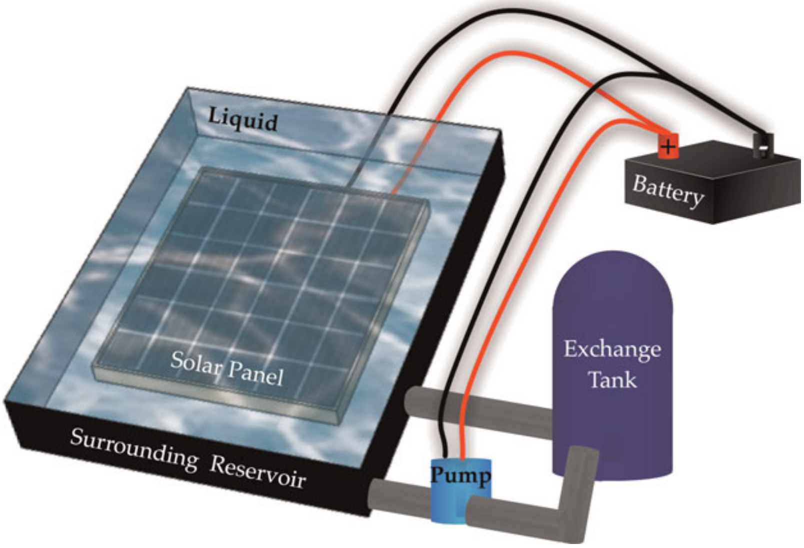

Fig. 5. The conceptual design inspired by the lichen model. [A color version of this figure can be viewed online at journals.cambridge.org/aie]

Returning to the lichen example, the principles of symbiosis, employed by the lichen as a whole, and photosynthesis, performed by the photobiont, are stored in the Design Repository. When the Design Repository is queried for solutions to the functionalities contained in a conceptual functional model derived from a set of customer needs, this biological system or others may be returned. A designer, when presented with the biological solutions of symbiosis physiology or the photobiont and mycobiont organisms, is subsequently required to review the provided biological information stored in the Design Repository to correlate the abstracted biological functionalities to familiar engineered functionalities. It is through this correlation of function that the designer can take inspiration from the biological systems.

4. DISCUSSION

Functional models provide a foundation for a systematic product design process that may be based on biological inspiration. Using the functional model as a starting point for concept generation provides two approaches for biology inspired engineering solutions. Following the first approach, a biological functional model drives concept generation. Engineering solutions in a design repository map to the functionality of modeled biological systems. This first approach assists with making the leap from biology to engineering and places the design connection process within the engineering domain, which is a familiar working environment for the designer. Following the second approach, a functional model is generated from customer needs; when a design repository is queried with those functions, biological solutions may be returned as potential options. This second approach places the design connection process within the biological domain, and requires the designer to analyze each of the biological results for potential inspiration. The first approach helped to link biology to engineering, but the second approach reverses this by assisting with the link from engineering to biology. Both approaches, however, allow a designer to systematically consider biological systems during the conceptualization phase of the product design process. We consider the methodologies and approaches to be successful when a designer can analyze a biological system through the creation of a biological functional model or the Design Repository entries and identify connections between biology and engineering through function that lead to inspiration of a concept.

The two concept generation approaches discussed above share similarities with the methods proposed by Vattam et al. (2008) and Chakrabarti and colleagues (Chakrabarti et al., 2005; Sarkar et al., 2008; Srinivasan & Chakrabarti, 2009*b*). In the approach proposed by Vattam et al., a designer first poses a design description. From this design description, a design question is posed in the terms of biology; this process is called “biologizing” the design problem. The “biologized” design question is used to seed the designers search of a biology-based problem space where inspiration may lead to compound, analogical designs. This is similar to concept generation approach 1 presented here in that both approaches start by first posing a design question based on a biological system of interest. Our approaches, however, rely on engineering and biological information stored in a design repository. Results from the design repository can, like in the approach of Vattam et al., lead to compound, analogical designs if multiple biological systems are returned for desired functions. Engineering solutions also may be mixed with the biological solutions in our approaches. A key difference between these approaches is the framework provided by our research. Vattam et al. take a freeform approach to biologically inspired design, but our methods and tools support the designer from the initial point of framing the design problem to translating and representing the biological information in an engineering context to completion of the concept generation phase. In the approach proposed by Chakrabarti et al., databases of natural and artificial systems are indexed by function, behavior, and structure. To achieve inspiration the designer uses the databases by defining the problem based on behavior-focused constructs that may match existing natural or artificial solutions or browse the database to gain understanding of how alternative natural and artificial solutions solve similar problems. This is similar to both of our approaches in that all three rely on a database populated with existing natural and artificial solutions. Our approach, however, uses multiple levels of abstraction based on categories and scales to capture different levels of function information related to biological systems. Our process also encourages the designer to explore biological systems outside those within the Design Repository, adding systematic exploration to chance observation and inspiration.

5. CONCLUSIONS AND FUTURE WORK

Using engineering design tools such as functional models and automated concept generators with biological systems can bridge the gap between the engineering and biology domains and can facilitate a designer use of biology's insights. Biological organisms operate in much the same way that engineered systems operate; each part or piece in the overall system has an intended function. Function thus provides a common ground. This research demonstrates that using functional models to describe biological systems can represent natural designs in an engineering context. Thus, biological information can be made accessible to designers with varying biological knowledge.

Viewing the biological system from an engineering perspective and breaking it down into manageable parts can clarify the parallels that exist between engineering and biology. Developing connections between these domains leads to inspiration for novel engineered solutions. Functional modeling holds the potential to provide a translator between these domains, but the task of generating a functional model of biological systems is not trivial. Five key points can help guide this process.

1. Cleverly defining the design question can aid with keeping the biological functional model from becoming too complex.
2. The category and scale of the model must be chosen carefully such that the model may be valid to the design question and accurate to the system.
3. The energies associated with the biological system must be defined appropriately using analogous engineered system equivalents.
4. Biological scale based on the detail of information provided is a good starting point, but when developing the final model, the scale must represent the design question originally posed.
5. Choosing a category serves to refine the boundary, but, like scale, it should be flexible through the concept generation process as it can allow a biological system to be considered in new and unique ways.

The two concept generation approaches presented in this research also point to a third hybrid approach that will be investigated in future research activities. In the hybrid approach, a biological system would be modeled functionally. The functional model of the biological system would be used to query a design repository, and new, similar biological systems that perform similar functions would be returned. With the hybrid approach, knowledge of the initial biological system modeled is required, and it is upon the designer to learn about the analogous biological systems returned from the database.

Concept generation helps to enable biological inspiration during the design process; however, it is still limited by the knowledge and skill of the designer and the database from which connections are drawn. To develop connections between the biological systems and engineered systems it is necessary to study the biological system either initially when making a functional model or during concept generation when biological systems are presented as possible design alternatives. It is important to understand that the approaches do not generate concepts; that is the task of the designer. However, they do provide opportunities for connections between the domains to be identified, so that it may be easier for the designer to make the final connections leading to biologically inspired designs. Future work will include a study to investigate when this leap is more feasible for an engineering designer. In addition, to make this work, the design process is heavily reliant on database content in both engineering and biological domains. To facilitate connection building, future research must include archival and maintenance of a repository of both engineering and biological solutions. We will continue adding biological systems into the Design Repository to continue improving the quality of solutions returned when using these methodologies.

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