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INTEGRATING FUNCTION-BASED AND BIOMIMETIC DESIGN FOR AUTOMATIC CONCEPT GENERATION

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ABSTRACT

This paper explores combining functional modeling and biomimetic design. Observed benefits of applying functional modeling to biomimetic design include a more complete, systematic modeling that reveals additional aspects of biological phenomena to be exploited. Incorporating biological phenomena into a function-based design repository requires that multiple facets of the potential solution be presented, including a natural-language description of the biological phenomenon, the strategy derived from the phenomenon, example implementation of the strategy in engineered solutions, and functional modeling of both biological and engineered systems.

This paper will illustrate the functional modeling of a single biological phenomenon at multiple levels of biological organization (organism/organ and cellular/molecular), the use of multiple biological analogies present in a single phenomenon in different engineering problems, and how the combination of functional modeling and biomimetic design leads to more complete exploitation of biological phenomena, as well as more complete representation of stimulus when including biological phenomena in a design repository.

Keywords: biomimetic design, automated concept generation, function based design

1 INTRODUCTION

The natural world provides numerous cases for analogy and inspiration in engineering design. From simple cases such as hook and latch attachments to articulated-wing flying vehicles, nature provides many sources for ideas. Though biological systems provide a wealth of elegant and ingenious approaches to problem solving, there are challenges that prevent designers from leveraging the full insight of the biological world. A fundamental problem is that the effort and time required to become a competent engineering designer creates significant obstacles to becoming sufficiently knowledgeable about biological systems to effectively execute biomimetic design.

In this paper, we describe a fundamental attempt to solve the knowledge requirement problem through the creation of a prototype biomimetic design repository. The design knowledge is stored based on the function the biological system solves as well as a natural-language description of the biological phenomena. We report the results of performing functional modeling of biomimetic design examples on the generation of additional concepts, compared with those generated using natural-language based biological stimuli alone. Key contributions include representing biological systems as solutions to desired functions, and increased discovery into the similarities and differences between biological and engineered systems.

2 BACKGROUND AND OBJECTIVES

2.1 Biomimetic design

The natural world contains some of the most elegant, innovative and robust solution principles and strategies. Biomimetic design aims to fully leverage the insight of the natural world into the engineered world by using analogies with biology to generate engineered solutions. Thus, at a more general level in engineering design, it is related to research in analogical reasoning, design by analogy, synectics, and TRIZ.

Analogical reasoning involves the transfer of information from a source domain, which contains the analogous phenomenon, to a target domain, which contains the problem to be solved by analogy (Vosniadou & Ortony 1989). Different types of similarity relate analogous items between the two domains. Surface similarity typically refers to superficial object attributes, e.g., colors, which are shared. Deep similarity is based on shared relational structures, e.g., flow of heat vs. flow of water (Gentner 1989), between two domains. Analogies can also be divided into two types based on relatedness between source and target domains. Within-domain analogies are used between the same or conceptually close domains, e.g., from one type of electromechanical product to another. Between-domain analogies are used between different source and target domains, e.g., from biological phenomena to electro-mechanical products.

Benami and Jin (2002) explored the relationship between the properties that stimulate cognitive processes and the design operations that facilitate cognitive processes. One conclusion of the study was that ambiguous entities stimulated more ideas than non-ambiguous entities, which tend to be fixating. Alternatively, between-domain analogies resulted in more creative, original ideas than within-domain analogies, which resulted in a greater quantity of ideas.

The Theory of Inventive Problem Solving (TRIZ) is a method used to trigger creativity in problem solving (Altshuller 1984). The foundation of TRIZ is the compilation and organization of technical knowledge through the analysis of patents. Recurring engineering conflicts and their solutions were identified and categorized into the TRIZ database. To use TRIZ, challenges of the design problem are matched with a list of engineering conflicts. Possible design principles are then suggested to overcome contradictions. Relevant to supporting biomimetic design, Vincent and Mann (2002) propose the extension of the TRIZ database to include biological information and principles.

In design by analogy, a number of design frameworks exist for facilitating the abstraction of within-domain analogies. McAdams and Wood (2000) developed a quantitative metric for design-by-analogy, which is based on the deep functional similarity of products within the domain of engineering. One goal of the metric is to reveal analogies between the functional requirements of the product to be designed and products that are similar, at a level that is useful for concept generation. Relationships between product functions and customer needs result in a procedure where critical functions of existing products can be adapted to solve the design problem of interest.

There are also knowledge-based systems that rely on surface similarity, such as Syn, where topological patterns of air circulation systems are matched with the requirements of the given architectural design problem (Goel 1997). More complex is the Ideal system developed by Bhatta and Goel (1994) that evaluates functional and causal patterns with no topological information such that deep functional similarities are explored.

Synectics is a technique for creative thinking that uses four types of analogies: direct, personal, symbolic, and fantasy (Gordon 1961). Biological analogies fall under direct analogies, and many design textbooks specify biological systems as a source of analogies (Dieter 2000, Ulrich & Eppinger 2000, Otto & Wood 2001, Hyman 2003, Dym & Little 2004). However, what remains unavailable to engineering students and practicing engineers are tools to formally support the identification and use of biological analogies for design.

2.2 Automated concept generation

Automated concept generation methods provide a unique opportunity to extend biomimetic design and integrate it fully into engineering design practice (Bryant et al, 2005ab; Kurtoglu and Campbell, 2005; Chakrabarti and Bligh, 1996). In the last three decades, concept generation has made significant advances from art to science, from the informal to the formal. Formal representations of products through structured data schema have enabled the creation of design repositories that allow designers to access solution principles that are outside their personal knowledge or expertise (Greer et al., 2003; Hirtz et al., 2002; Bohm and Stone, 2004; Bohm et al., 2005).

Automated concept generation is accomplished by at least two significantly different approaches – search and retrieval of analogous solutions by 1) a structured functional descriptor or 2) by natural-language processing. Inherent to the function-based approach is the recognition that devices are designed to solve specific functions. Thus, specifying and modeling the desired function of a product or system is fundamental in the conceptual design process. The ability of functional representation to allow designers to access such design information is a key strength of extending biomimetic design through the method of functional modeling. By contrast, natural-language processing imposes fewer restrictions on how biological (in this specific case) solutions are archived, searched and retrieved. In many cases, a search of textual descriptions of biological phenomena (perhaps from standard texts or journals) can be used to identify appropriate analogical solutions.

Recently, researchers have formulated automated concept generation techniques that rely on structured functional descriptors (Bryant et al., 2005b; Kurtoglu et al., 2005a; Attaluri et al., 2006). The research culminated in a suite of computational design tools at the center of which is a concept generator able to generate concept variants from a functional description of a product. The concept generator consists of two techniques that utilize archived product information in the design repository to synthesize new concepts. The technique relevant to this work expresses the product functionality-to-component relationships and component-to-component compatibility (e.g., whether two components can be connected together, based on the observations within the repository dataset) as matrices and mathematically computes all potential concept variants based on designer-specified desired functionality of a product. With this tool, a design team is able to rapidly generate and evaluate multiple and feasible design configurations that include choice of components and their connections (Bryant et al., 2006a,b).

Chakrabarti et al. (2005) develop a model for representing causality of natural and artificial systems to structure information in a database to support an automated analogical search of relevant ideas from the databases to solve a given problem. In contrast, we aim to combine two well-developed and proven methodologies: one in automated concept generation, and one in the identification and use of relevant biological analogies in natural-language format.

2.3 Objectives

One objective of this work is to integrate biological solutions into an existing design repository hosted at the University of Missouri-Rolla in both a function-description form and natural-language form. This portion of the research provides a mapping for biological phenomena to engineering design functional descriptions. Another objective is to compare the effect on concept generation of functional modeling versus concepts generated from natural-language stimulus only.

3 METHODS

The results of past case studies in biomimetic design are used to explore the effect of functional modeling on biologically inspired solutions. These case studies include those in design for remanufacture (Hacco and Shu, 2002), clean clothes (Mak and Shu, 2004), and microassembly (Shu et al., 2006). Several analogies from multiple levels of biological organization (e.g., molecular, cellular, ecosystem) were located in natural-language format for each case study. In this paper, functional modeling is performed for a single biological phenomenon common to all three case studies, but at different scales, from the organism/organ to the cellular/molecular.

3.1 Remanufacture of products with snap-fit joints

3.1.1 Problem description

Products with snap-fit joints, e.g., toner cartridges, present challenges to remanufacture when snap-fit features fail since they are difficult to repair in a reliable manner. Using threaded fasteners in the original design or subsequent repair lessen this difficulty, but threaded fasteners are favored by neither design for assembly nor design for recycling.

3.1.2 Biological phenomenon

Searching Purves et al. (2001) for "repair" resulted in the following match, describing how plants sacrifice and replace, rather than repair damaged organs such as leaves.

> The defense systems of plants and animals differ. Animals generally repair tissues that have been infected. Plants, on the other hand, do not make repairs. Instead, they seal off and sacrifice the damaged tissue so that the rest of the plant does not become infected. This approach works because most plants, unlike most animals, can replace damaged parts by growing new stems, leaves, and roots.

3.1.3 Strategy

The strategy derived from the above natural-language description is that it may be preferable to designate product features that are prone to damage as sacrificial, such that they can easily be replaced, rather than invest resources in a repair that may not result in a reliable part.

3.1.4 Previous solution

Our previous incorporation of this strategy into the design of a snap fit is as shown in Figure 1. Figure 1a shows a redesigned snap-fit configuration with a countersink and predetermined breakpoints. Figure 1b shows the redesigned snap fit after failure and repair with a replacement part. In the redesigned snap fit, the breakpoints cause the snap feature designated as sacrificial to break off, such that planned replacement parts can be used to more reliably repair the snap fit. The counter sink also helps to locate and secure the replacement part.

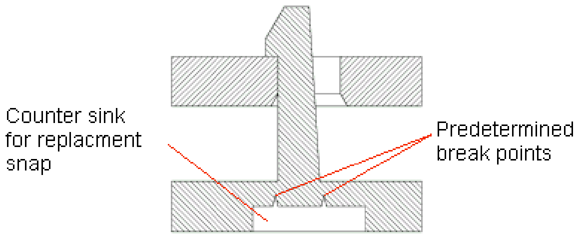

Figure 1a. Snap fit redesigned with countersink and break points

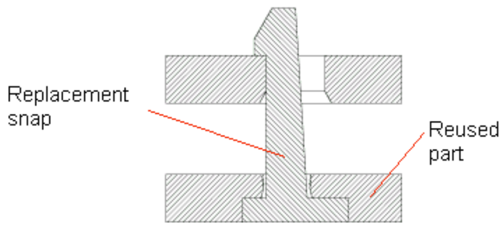

Figure 1b. Redesigned snap fit after failure and refurbishment

3.1.5 Functional modeling of biological phenomenon

The functional modeling of this biological phenomenon at a high (organ/organism) level is illustrated in Figure 2. The incoming material consists of the affected portion of the plant, and the outgoing material consists of the remaining portion of the plant and the dead leaf or other organ. The function that links the flow of material is "separate solid".

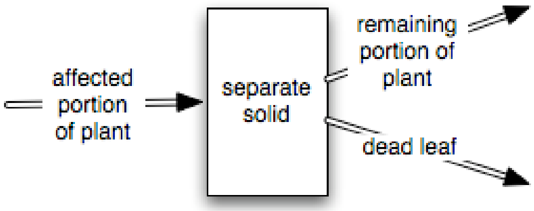

Figure 2. Functional modeling of plant sacrificing leaf

3.1.6 Functional modeling of engineered solution

The functional modeling of the reconfigured snap-fit solution based on this biological phenomenon is shown in Figure 3. The incoming material consists of the failed snap fit, analogous to the portion of the plant affected by disease. The outgoing material consists of the failed snap feature, analogous to the dead leaf or other organ. To solve the original problem, the outgoing material must also include the repaired snap fit, which necessitates supplying a replacement snap feature.

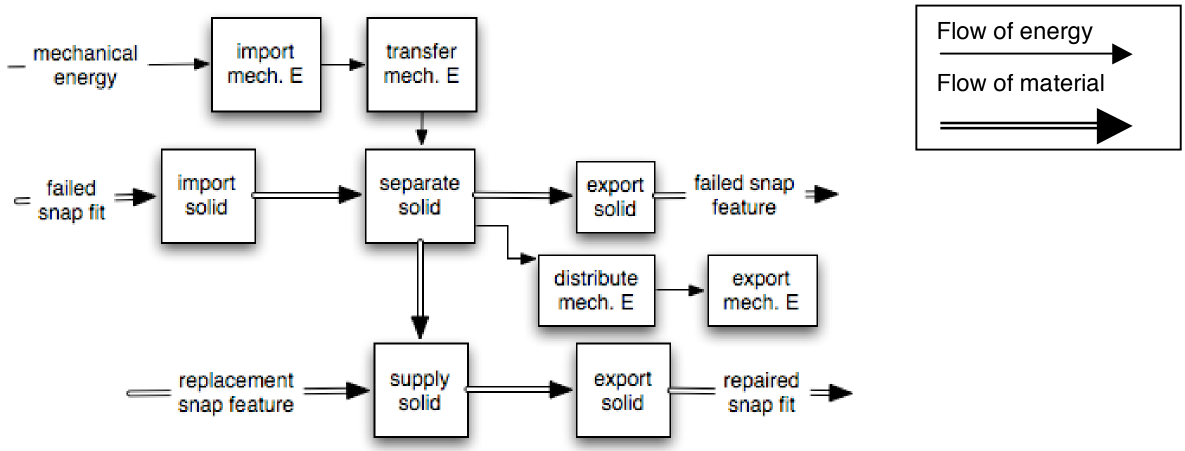

Figure 3. Functional model of repairing failed snap

3.2 Concepts to enable clean clothes

3.2.1 Problem description

The biological phenomenon described in natural-language format in Section 3.1.2 was presented to engineering students as stimulus to develop concepts that would enable clean clothes without focusing on the redesign of washing machines (Mak and Shu, 2004).

3.2.2 Previous solution

The solution that many students developed based on the natural-language stimulus involves removable patches of clothing that can be removed and replaced when they become dirty.

3.2.3 Functional modeling of engineered solution

A high-level functional modeling of the clean-clothes solution is shown first in Figure 4, where the incoming material consists of the soiled clothes, and the outgoing material includes the clean clothes as well as dirty patches. Similar to the failed snap fit example, the function connecting the material flow is "separate solid". More detailed functional modeling of the clean-clothes concept is also shown in Figure 4. To address the original goal of providing clean clothes, an additional subfunction that must be fulfilled is "supply solid", referring to the furnishing of clean clothing patches.

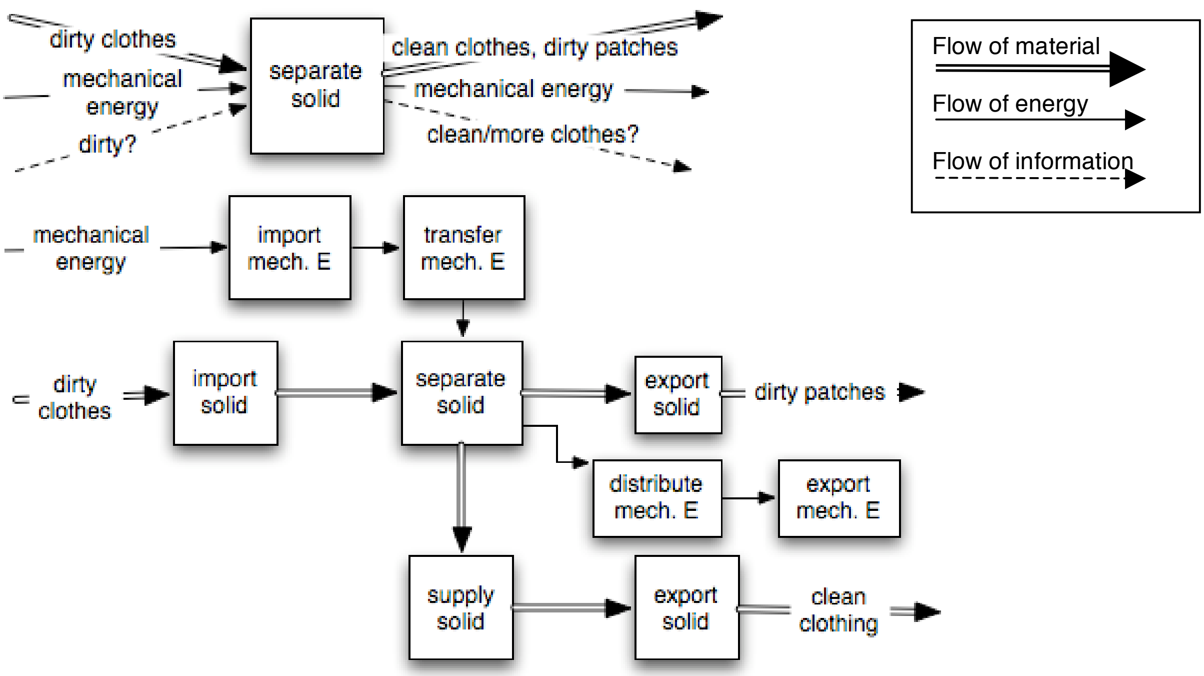

Figure 4. Functional modeling of clean-clothes concept

3.2.4 Additional ideas resulting from functional modeling

The previous concepts based on the biological phenomenon focused on the sacrificing of the dead or failed feature/region. That is, rather than expend resources on repairing tissue/feature/fabric, the leaf/snap feature/clothing region is replaced. Examining the functional models of the snap-fit and clean-clothes solutions reveals that just as important to the concept is that the replacement snap feature or clothing patch be supplied. The original natural-language description makes reference to the "growing" of replacement organs. While it may not be practical for a product to literally "grow" replacement features for failed or dirty parts, it is possible to consider how such replacement parts may be integral to the product, and perhaps how the failure and removal of the broken feature may work towards the positioning of the replacement part. In the clean-clothes example, multiple layers could be provided in dirt-prone areas, e.g., elbow patches, where the removal of the top layer reveals a clean layer underneath. In the snap fit example, it may be possible to configure a snap feature that when removed, pulls another feature into place, similar to how the removal of the top tissue from a tissue box pulls into the position the next tissue because of how tissues are folded into each other. Performing and examining the functional model highlight additional requirements, and lead to generation of concepts that satisfy them.

3.3 Release of microscrew during microassembly

3.3.1 Problem description

In microassembly, surface forces that dominate gravitational forces, resulting in sticking between microgripper and micropart, complicate the release of parts from a microgripper.

3.3.2 Biological phenomenon

Searching Purves et al. (2001) for "break down", a biologically connotative keyword for "remove/release" located the following analogy that describes how the abscission process provides a mechanism for release of leaves by plants. While it is interesting that the micro scale of the problem situation matches well with the macromolecular and cellular level details of the plant-organ loss phenomenon, this matching of scales was not intended during the search.

> Abscission is the process by which leaves, petals, and fruits separate from a plant. Plants direct growth in different parts such as roots and shoots by strategically releasing a hormone called auxin. When leaves are damaged through infection for example, or are no longer needed, as in the winter season, the leaves stop producing auxin, allowing the further expression of abscisic acid and ethylene, which advance abscission. As a result, specific parts of the stalks of the leaves break down and become completely detached from the plant. The base of some leaves contains a special layer of cells called the abscission zone. In the absence of auxin, these cells swell and form a cork-like material. This cuts off the flow of nutrients to the leaf and forms a seal between the leaf and the plant and protects the plant once the leaf separates (Purves et al., 2001).

3.3.3 Strategy

The strategy derived from the above natural-language description is that an intermediate (abscission) zone facilitates the separation of parts.

3.3.4 Previous solution

A previous generic incorporation of this strategy for the release of a micropart is shown in Figure 5, where a sacrificial part of either the gripper or micropart is used to add mass, such that gravitational forces will dominate surface forces in the release of the combined sacrificial part and micropart. This sacrificial part is then broken down either chemically or thermally after the micropart is positioned.

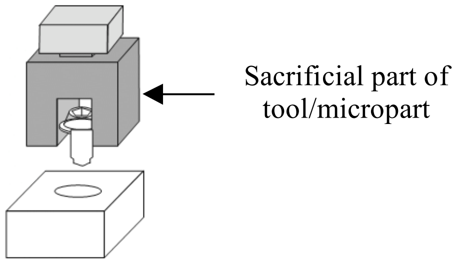

Figure 5. Sacrificial part of tool corresponding to abscission zone

A sacrificial part that must be broken down chemically or thermally introduces not only another process in the assembly of the micropart, but likely also undesired contaminants. Another interpretation of the sacrificial part was implemented and tested at the Technical University of Denmark, and is shown in Figure 6. The abscission zone is physically represented as a polypropylene rod of 4 mm diameter that is easily gripped and positioned by a standard industrial robot without end effectors required for the manipulation of microparts. The tip of the polypropylene rod is locally melted by a heating plate, and then pressed over the head of the screw. During solidification of the polypropylene, a solid bond between the rod and the screw is formed. The robot can then manipulate the screw into the plastic counterpart. Once the screw is tightened into its final position, the resulting increased torque breaks the bond between screw and rod.

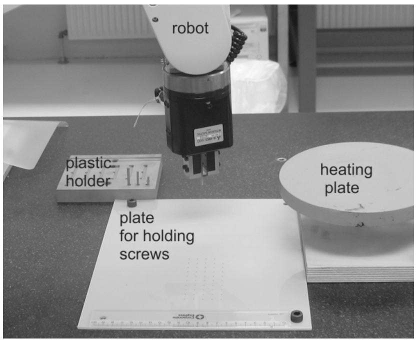

Figure 6a. Experimental setup for validating the abscission-based release of microparts

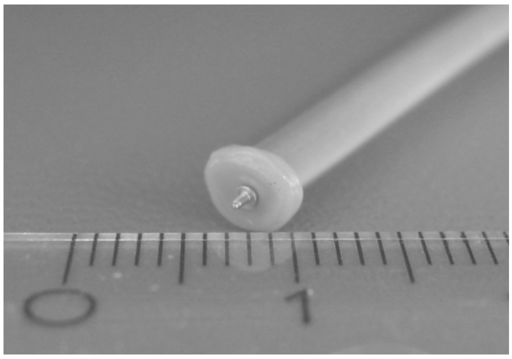

Figure 6b. A microscrew embedded into a polypropylene rod that can be handled by standard industrial robot

3.3.5 Functional modeling of biological phenomenon

Figure 7 shows the functional modeling of the same biological phenomenon, separation of dead leaf from plant, at a lower (cellular/molecular) level. This model reveals that in addition to the separate-solid, import-solid and export-solid functions present in the concepts inspired by the same biological phenomenon at the organism/organ level, at the cellular/molecular level, the regulate-flow function leads to the separation of a dead leaf from the remainder of the plant.

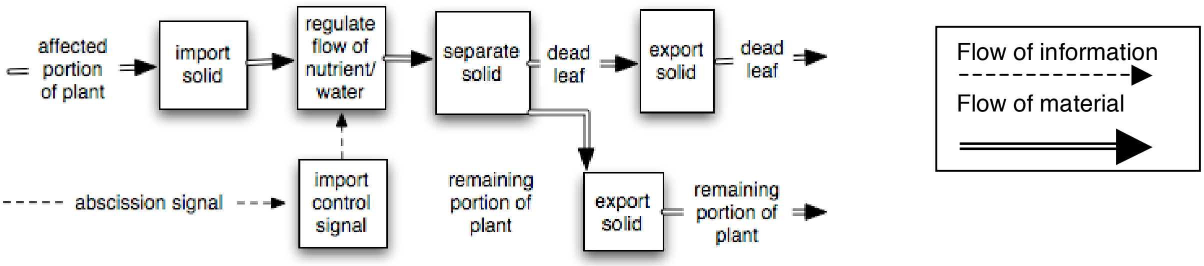

Figure 7. Functional modeling of abscission phenomenon

3.3.6 Functional modeling of engineered solution

The functional modeling of the engineered solution based on this biological phenomenon is shown in Figure 8.

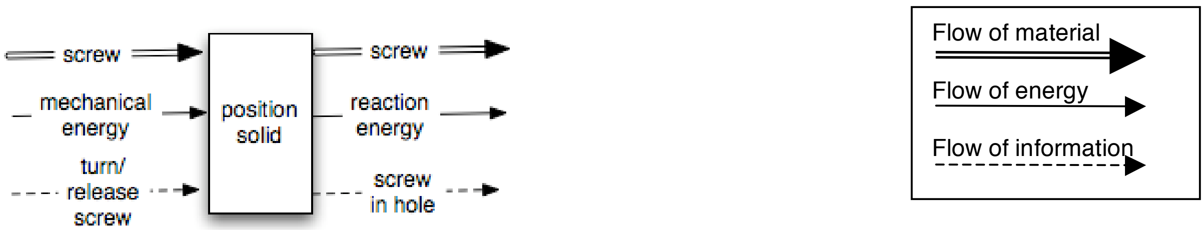

Figure 8a. High-level functional modeling of microscrew handling and insertion solution

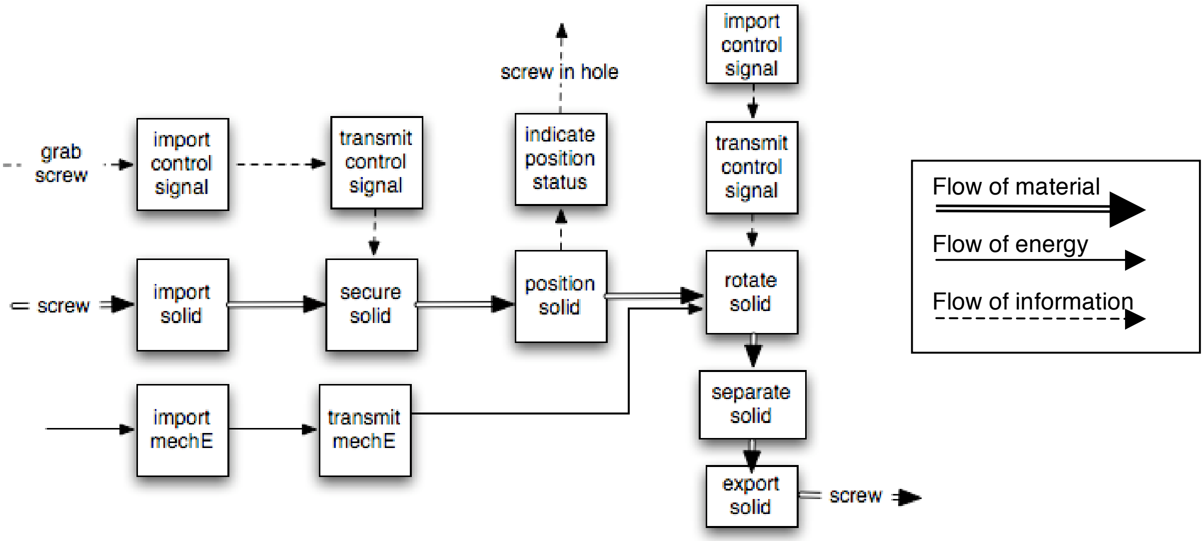

Figure 8b. Detailed functional modeling of microscrew handling and insertion solution

3.3.7. Additional ideas resulting from functional modeling

In this case, further examination of the functional model for the biological phenomenon provides insight into the engineering solution. Specifically, the regulation of hormones, nutrient and water, central to the abscission phenomenon suggests that parameters must also be regulated in the microassembly solution. Indeed, while verifying that the polypropylene rod incorporated as described above can be used to manipulate the microscrew into position, it was found that the temperature of the heating plate is the most crucial parameter. At too low of a temperature, the rod is not sufficiently melted, and the bond between the rod and screw is not strong enough for successful tightening of the screw in the substrate. At too high of a temperature, the melted polypropylene flows into additional features in the screw such that the increased torque once the screw is fully tightened is not enough to separate the rod from the screw – an additional pull force must be applied.

The functional model for the biological phenomenon also suggests the possibility of a suction-based approach. Instead of regulating the flow of nutrient/water, an engineered solution could regulate flow of a gas, e.g., use suction to retrieve and possibly orient a microobject, and reverse pressure to release. In addition, an electromagnetic approach can be used on microobjects that can be magnetically polarized, where the magnetic field of the tool could be reversed to separate tool from microobject.

4 SUMMARY

This paper explored combining existing and proven methodologies in functional modeling and biomimetic design. Observed benefits of applying functional modeling to biomimetic design include a more complete, systematic modeling that reveals additional aspects of biological phenomena to be exploited. Incorporating biological phenomena into a function-based design repository requires that multiple facets of solution be presented, possibly including a natural-language description of the biological phenomenon, the strategy derived from the phenomenon, example implementation of the strategy in engineered solutions, and functional modeling of both biological and engineered systems.

This paper illustrated the functional modeling of a single biological phenomenon: the shedding of diseased or dead leaves by plants at multiple levels of biological organization (organism/organ and cellular/molecular). This single phenomenon led to solutions for previous case studies. Examining functional models of the biological or engineered solutions for these examples led to more complete exploitation of biological phenomena, which suggests the need for more complete representation of stimulus when including biological phenomena in a design repository.

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