Biomimetic Design to Enable Sustainable Product Development

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Abstract
Sustainable product development requires innovation that may benefit from biological models. While many examples of biomimetic design exist, how the specific biological models were selected is often unclear. Chance knowledge, or use of the most obvious biological phenomena does not take advantage of the wealth of information possible, thus limiting innovation. This paper outlines a methodology to identify relevant biological analogies for any given design. Instances of keywords describing the intended effect of a design solution are located in biological knowledge in natural-language format. An example involving remanufacture illustrates application of this methodology to an aspect of sustainability.

Keywords:
Biomimetic design, remanufacture, sustainability

1 INTRODUCTION

There are many elegant solutions to engineering problems that were inspired by biological phenomena. The potential of biomimicry to help solve environmental problems has also been proposed [1]. Most work in biomimetic design involves specific cases of design that copy particular biological models, where it is not always clear how particular biological models were identified or selected. Therefore, an engineer open to using biological models for design may not know how to find relevant biological analogies for a given design. In addition, the use of the most obvious biological phenomena that come to mind may not lead to the most innovative solutions.

This paper describes a systematic method by which biological analogies can be identified and used for any given design problem, including those that improve sustainability, in an objective and repeatable manner. The approach chosen is described.

A problem in design for remanufacture is used to illustrate application of this methodology to an aspect of product sustainability. Brief background on remanufacture is provided, followed by some obstacles to design for remanufacture. Finally, the identification and use of biological analogies for this problem involving remanufacture are described.

2 METHODS

2.1 Approach

A possible approach to support generalized biomimetic design is to build a database of biological phenomena for engineering use [2]. The approach described here differs fundamentally and avoids the extensive and possibly subjective task of cataloguing biological phenomena for engineering purposes. Instead, this method takes advantage of the abundance of biological information already available in natural language format by searching it directly for relevant phenomena.

This approach has been implemented as a computerized search tool that locates in biology texts occurrences of functional keywords that describe the engineering design problem.

2.2 Source

Life, the Science of Biology [3], the reference text for the introductory course in biology at the University of Toronto is selected as the initial source of information. This text is suitable because it is written at a level that can easily be understood by those with little background in biology. The text also covers a large range of organizational levels, from the molecular and cellular, e.g., DNA, to the ecosystem, such that potential solutions are not limited to a particular organizational level.

2.3 Keywords

Keywords used to find relevant phenomena are verbs that describe the desired effect of possible solutions. Verbs are typically preferred over nouns as keywords. Searching for nouns frequently indicates pre-conceived solutions while searching for verbs that describe the desired action will identify biological forms that may not have occurred to the designer.

3 REMANUFACTURE

3.1 Background

Bras and McIntosh provide an overview of research in remanufacture [4]. Remanufacture is a process applied to products at their end of life that seeks to reuse product components. Lund outlines advantages of remanufacture over recycling for scrap material that include conservation of resources required to melt and reform components [5]. Shu and Flowers identified a design guideline to facilitate remanufacture as 'product features that are prone to failure should be made separable.' In this way, the failed features can be replaced, enabling the reuse of a component without labor- and capital-intensive repair operations. However, making failure-prone features separate increases part count and assembly cost [6].

3.2 Example problem

Snap fits enable fastening without introducing additional parts or materials, and are thus often preferred for assembly and recycling purposes. However snap fits are problematic for remanufacture when they fail because they are difficult to repair. Figure 1 shows a failed toner-cartridge component undergoing remanufacture that contains a snap fit. Biological phenomena analogous to remanufacture were sought to address this problem.

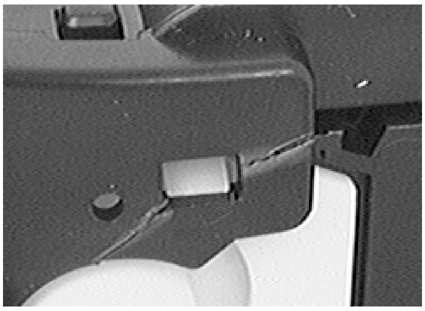


Figure 1: Damaged part with snap-fit [6]

4 BIOLOGICAL ANALOGIES FOR REMANUFACTURE

Searching for the keyword ‘remanufacture’, not surprisingly, resulted in no matches in the biology text. Thus, alternative keywords such as synonyms are required to find matches. Other keywords including ‘repair’, ‘correct’ and ‘restore’ located analogies at the molecular, organ/organ system/organism and eco-system levels of biological organization.

After identifying relevant biological phenomena, the strategy used in each phenomenon to solve an analogous problem is extracted and applied to the engineering problem. Generalized strategies are described for each biological phenomenon listed below.

Illustrated below are examples of both analogical *carry-over*, where a novel solution is developed based on the biological phenomenon, and analogical *matching*, where the biological phenomena is matched to a known solution. However, whether carry-over or matching occurs depends on the state of knowledge of the person using the biological phenomenon. That is, what is known practice to one may be a novel idea to another, and vice versa.

Finally, application of the generalized strategies of the phenomena to the snap fit problem is described.

4.1 Molecular: DNA repair mechanisms

Matches identified using ‘repair’ involve DNA repair mechanisms, including DNA proofreading during replication, mismatch repair and excision repair. Excision repair was found to be the most analogous to repairs performed during remanufacture. Text on excision repair follows [3]:

> An excision **repair** mechanism removes abnormal bases that have formed because of chemical damage and replaces them with functional bases.
>
> ... in excision **repair**, certain enzymes “inspect” the cell’s DNA. When they find mispaired bases, chemically modified bases, or points at which one strand has more bases than the other (with the result that one or more bases of one strand form an unpaired loop), these enzymes cut the defective strand. Another enzyme cuts away the bases adjacent to and including the offending base, and DNA polymerase and DNA ligase synthesize and seal up a new (usually correct) piece to replace the excised one.

Although the occurrences of ‘repair’ in the matches are adjectives and nouns, they are still relevant to the verb ‘repair’ sought. Also, while the above excerpt confirms relevance of the excision repair phenomenon to remanufacture, the text does not provide ideas to solve our problem. Further research using a more advanced text by Friedberg et al. [7] reveals that ‘a conformational change’ in the DNA enables the removal and replacement of the bases in the affected segment.

Generalizing for product design, a conformation change associated with failure can be used to facilitate the removal and replacement of faulty components [8].

4.2 Organism: Sacrifice and regeneration of parts

The ability of plants to grow new parts to replace damaged parts was identified as an analogy at the organ/organism level. The relevant section follows [3]:

> The defense systems of plants and animals differ. Animals generally **repair** tissues that have been infected. Plants, on the other hand, do not make r**epair**s. 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.

Applying this analogy to products involves incorporating a sacrificial part that can be replaced such that repairing the broken feature or replacing the entire part that contained the feature can be avoided.

For example, Figure 2, from the repair manual of a photocopier remanufacturer, shows the inside features of a photocopier door that is opened to remove a paper jam. In the process of clearing the paper path, several levers are moved. These levers must be replaced before another photocopy is made. The function of the cone shown is to prevent the door from being closed without having first replaced the levers. Due to its function, the cone is frequently damaged. During remanufacture, a portion of the damaged cone is cut away and a new cone is glued on.

To facilitate this process, the door could be designed with features to assist the fitting or installation of planned replacement parts. For example, the inclusion of perforations at the dotted line shown in Figure 2 that indicate the location where the damaged feature is cut away would facilitate disassembly of the damaged feature. Of possible interest are abscission mechanisms that aid in separation of leaves and fruits from plants.

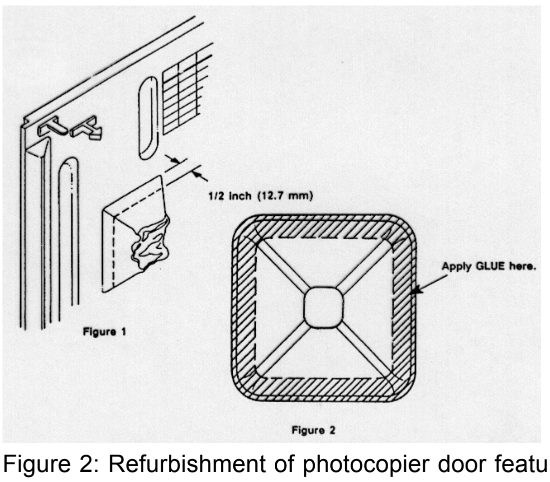


Figure 2: Refurbishment of photocopier door feature

Generalizing this strategy, features likely to fail should be made as sacrificial parts, and be replaced rather than repaired.

4.3 Ecosystem: Forest restoration

The keyword 'restore' identified the following excerpt describing the restoration of tropical forests [3]:

> The world's largest restoration project is under way in Guanacaste National Park in northwestern Costa Rica. Its goal is to **restore** a large area of tropical deciduous forest – the most threatened ecosystem in Central America – from small fragments that remain in an area converted mostly to pastures.

The concept to be used from this analogy is that restoration involves a process that builds upon a foundation or substrate of small fragments of preserved forest until they meet to form a large continuous forest. An analogous concept can be used for restoring parts in remanufacture.

For example, Figure 3, from the manual of a photocopier remanufacturer, shows a repair method for a photocopier panel that requires the embedding of mesh substrate into a section with a hole. The screen acts as support for filler material to replace the lost material. That is, replacement material bonds onto the screen, and more replacement material is bonded until a continuous panel is restored. The correct positioning of this screen in the panel is important for the structural and aesthetic results of the repair. Design that facilitates this process further could involve incorporating locating features for a possible replacement screen in portions of the product that are likely to fail, so that effort need not be expended in positioning the screen during remanufacture.

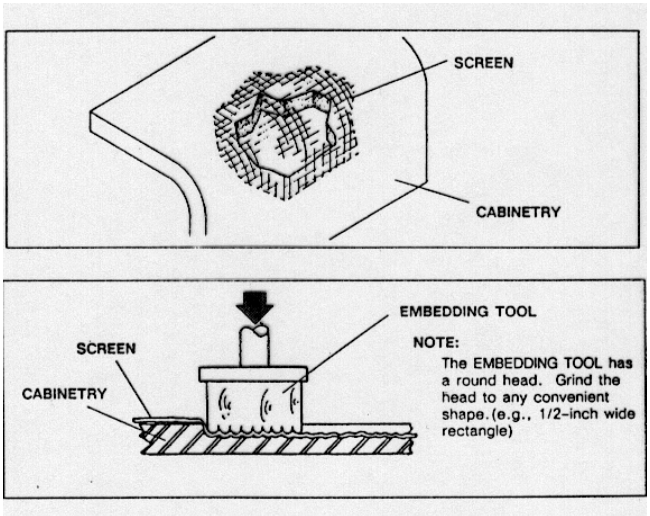


Figure 3: Refurbishment of photocopier panels

To generalize, providing a base or substrate upon which anticipated repairs may build facilitates repair or replacement of failed parts. Furthermore locating features reduce efforts required to position a replacement part.

4.4 Organ system: Fainting

Another phenomenon identified using the keyword 'correct' involves fainting. The text regarding fainting follows [3]:

> Blood must be returned from the veins to the heart so that circulation can continue. If the veins are above the level of the heart, gravity helps blood flow, but below the level of the heart, blood must be moved against the pull of gravity. If too much blood remains in the veins, then too little blood returns to the heart, and thus too little blood is pumped to the brain; a person may faint as a result. Fainting is self-**correct**ing: A fainting person falls, thereby moving out of the position in which gravity caused blood to accumulate in the lower body.

The concept derived from the above excerpt is that fainting is a form of defensive failure that prevents more serious failure. Generalizing to product and part design, features could be included that induce failure modes that are easier to repair.

5 CONCEPT DEVELOPMENT

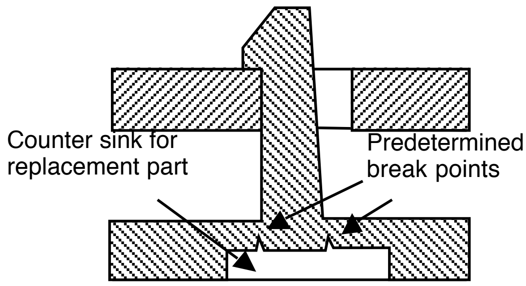
Figure 4 shows a redesigned snap fit where a part containing a failed snap fit feature can be more easily reused. This redesign incorporates the strategies identified above from analogous biological phenomena.

From DNA excision repair, a configuration change associated with failure enables repair processes, specifically removal and replacement of faulty components. In the redesigned configuration, failure of the snap fit feature leads to its removal, clearing the way for replacement of the feature.

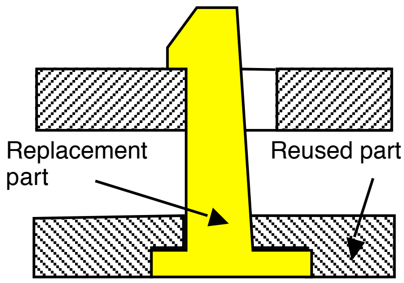
From the ability of plants to seal off and sacrifice old parts, new replacement parts are generated instead of repairing the damaged part. In the redesigned configuration, the failed snap fit feature constitutes a sacrificial part that is replaced rather than repaired.

From forest restoration, the rebuilding of parts may benefit from a substrate or other structure that supports and locates the replacement part. Figure 4 shows the countersink that would help support as well as locate a replacement part.

Applying the fainting strategy to the redesign, predetermined breakpoints incorporated into snap fit configurations may cause earlier failure than with standard snap fit configurations, but may also induce failure along predicted locations such that the part is easier to repair. Figure 4 shows predetermined break points that may serve such a purpose.



a. Snap fit redesigned with counter sink and break points



b. Redesigned snap fit after failure and refurbishment

Figure 4: Redesigned snap fit to facilitate repair [9]

6 SUMMARY AND FUTURE WORK

This paper described a systematic method to identify and use biological analogies for any given engineering design problem. An example in design to facilitate remanufacture at product end of life is used to illustrate the methodology applied to improving one aspect of product sustainability. This example involved snap fits that are desirable for assembly and recycling purposes, but cause problems for remanufacture because failed features are difficult to repair.

Instances of keywords and synonyms including repair, restore and correct, were used to locate biological phenomena at the molecular, organ/organ system/organism and ecosystem levels. Phenomena identified include DNA excision repair, plants sacrificing diseased parts and regenerating new parts, tropical forest restoration, and fainting. The strategy of having failure-induced conformation change facilitate removal and replacement of defective features was derived from the DNA excision repair phenomenon. The ability of plants to sacrifice and regenerate parts led to the strategy of sacrificial parts or features that are replaced rather than repaired. Ecosystem restoration led to the strategy of providing a substrate to support as well as locate possible replacement parts necessary for repair. Finally, the fainting phenomenon led to the strategy of incorporating features that encourage possibly premature failure in a predictable direction such that the part is more easily repaired after such failure. These strategies were then incorporated into a redesigned snap fit configuration that would facilitate the repair and reuse of parts that contain a failed snap fit.

In addition to remanufacture, another application of this biomimetic design method involved finding and using biological analogies for the task of centering in micro assembly [10]. Different from the remanufacture example, most analogies located for the centering problem were at the cellular level, although all levels of biological organization were searched.

Current work of a more fundamental nature examines language analysis and analogical reasoning relevant to biomimetic design. Natural language analysis is used to summarize dominant biological phenomena associated with keywords [11]. Since the total number of matches can be unmanageable, a summarizing mechanism reduces the amount of effort required to identify promising biological phenomena. Analogical reasoning is required to recognize, extract, and apply strategies used in biological phenomena to engineering design problems [12]. Studies were performed to investigate cognitive difficulties associated with using analogies for design [13].

The author is actively seeking and would welcome other case studies for biomimetic design, including those concerning product sustainability as a basis for collaboration.

7 ACKNOWLEDGMENTS

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