ABSTRACT

Title of Thesis:	FUNCTION BASED ARCHIVAL AND RETRIEVAL: DEVELOPING A REPOSITORY OF BIOLOGICALLY INSPIRED PRODUCT CONCEPTS
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Many new product concepts have been developed by using inspiration from the biological world. These bio-inspired concepts offer many advantages in the development of engineered products and devices. However, there exist difficulties in locating promising sources for bio-inspiration. This thesis describes the development of an open repository of biologically inspired product concepts that will provide engineers access to a new resource for design ideas and examples. The current repository contains 89 different biologically inspired products, and new product concepts can be submitted to the repository by their developers. In order to make these design concepts more accessible, a new and easy-to-use method of function based archival and retrieval was developed – the Functional Description Template. This method can be used to archive functions of all classes of products, but is used in this application for bio-inspired products and biological systems. The Functional Description Template uses an extensible functional language to record product functions so that they are more expressive and complete while still being computer interpretable. In order to evaluate this new method, a

study was conducted that offers a direct comparison to a Functional Basis, an alternative approach to archiving functions. The evaluation showed that the Functional Description Template method allowed greater expressiveness and completeness in the user's recorded functional statements. Using the Functional Description Template method, the participants in the study recorded more matched terms, averaging an increase of 29 matched terms, and lost less functional information, averaging 7 fewer pieces of information lost. Also, the participants improved their correctness in recording their functions by an average of 23%. Evaluation forms completed by the participants also indicated that the Functional Description Template was easier to use and more accurate in recording the user's functions. In addition to the Functional Description Template, flexible search tools were proposed for the repository, which facilitate a content-based search of the products and concepts. Users can search for products that satisfy functions of similar meaning, but are stated with different terminology. Several different search criteria can also be used to retrieve the concepts available in the repository. This complete system offers a step towards improving the product development process by including bio-inspiration in future product design.

FUNCTION BASED ARCHIVAL AND RETRIEVAL: DEVELOPING A REPOSITORY OF BIOLOGICALLY INSPIRED PRODUCT CONCEPTS

By

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Chapter 1: Introduction

The work presented in this thesis describes the development of a system for helping engineers to locate design concepts in nature for the development of products and devices. In order to make these design concepts more accessible, a new method of archiving and retrieving functions has been developed as part of this system. This method, called the Functional Description Template, is a functional language that allows users to describe the functions of any product or biological system in a more expressive and complete way. The goal of this method and the complete system is to help improve product development. Before elaborating on this work, some background knowledge is required in both engineering product development and bio-inspired engineering.

1.1 Engineering Product Development

In developing a system to help engineers locate design concepts it is important to understand the role such a tool will take in the product development process. The engineering product development process can be divided into a number of steps. These steps include the following initial steps:

1. Define the problem
2. Determine customer needs
3. Identify functional requirements
4. Generate design concepts

The goal of the work described is to improve the concept generation phase of product development. Concept generation is the point in the product development process where

ideas are formed and the product begins to take shape. When generating concepts for a product, design concepts are usually identified for each of the functional requirements that were established in the previous step. These concepts are then integrated into a final product design. In order to improve concept generation, one must understand where these concepts are found.

Engineers search for possible design concepts using a variety of methods. A common practice is brainstorming, an internal search for ideas. However, more commonly, a search is conducted using search tools that access an external knowledge base, whether it is the Internet, a library, or a database of information like TRIZ. Regardless of the method, an engineer is usually searching for existing products or concepts that satisfy a set of functional requirements. Most design problems are solved by applying existing ideas in a new way. The searches that are conducted examine a design space of existing solutions. This design space includes existing engineered products and devices and any experience or knowledge of the engineer. However, this information is primarily from the engineering world, where these products were developed and where engineers receive their education and training. In order to increase the potential for generating new design concepts, the design space should include as much knowledge as possible. An abundant source of designs exists in the natural world. The design tool that has been developed seeks to meet this objective of improving concept generation by making design concepts from nature more accessible to engineers. By including nature in the engineers design space, many new concepts may be developed for products, and the field that has come to be known as bio-inspired engineering will begin to grow.

1.2 Bio-Inspired Engineering

Bio-inspired engineering is engineering that takes inspiration from nature. Engineers are frequently asked to design new materials, structures, mechanisms, and processes. To design these new products and artifacts often requires a search for new ideas. Bio-inspired engineering looks to nature for new ideas. Often, these concepts that are found in nature can be mimicked. Thus, bio-inspired engineering is sometimes referred to as biomimetics. In some instances, however, it is more beneficial to take inspiration from nature's creations rather than mimic them directly.

By looking to nature for solutions, new and innovative designs are being developed in robotics, aerodynamics, biomedical devices, materials, and computing. Engineers are now able to study the materials and geometry of biological structures, the sensors and processing of biological control systems, and the kinematics of biological locomotion. Using this knowledge, bio-inspired concepts are becoming more prevalent in engineering product development.

1.2.1 Brief History

The strategy of biologically inspired design has been employed for thousands of years, and biomimetics, in some form or another, has been around for much longer. People have always looked to nature for inspiration. The earliest known example of biologically inspired engineering can be traced back about 3,000 years, when the Chinese attempted

to create artificial spider silk in order to produce cheaper cloth. The Chinese never succeeded; even today we are unable to replicate spider silk.

One of the earliest cases of biologically inspired design is that regarding flight. When humans attempted to set to the skies, the only example we had of flight was birds. Many early attempts were made at flight by designing some sort of flying device that mimicked the structure of birds. The earliest known example is the myth of Daedalus' wings. Daedalus constructed wings out of a wooden frame and attached feathers. Despite the failure of this device, the myth of Daedalus set the stage for many future attempts at flight. The successful flight by the Wright Brothers used a plane that was modeled after the structure of bird's wings. And even today, aerospace engineers are improving the aerodynamics of aircraft by mimicking features of birds.

As engineering has developed in the past hundred years, so have bio-inspired practices. Some examples include the Crystal Palace, the Eiffel Tower, and Velcro. Around 1850, Joseph Paxton designed the Crystal Palace, shown in Figure 1, based upon the support structure of the Victoria Amazonica lily. The leaves of this flower inspired Paxton's self-supporting glass roof.

Figure 1: Victoria Amazonica lily (left) [McRo99] and the Crystal Palace (right) [Wein99]

Around the same time, Karl Cullman applied to the Eiffel tower the principle of building along lines of force for non-centralized structures. This concept was first studied by Hermann von Meyer in the head of the femur bone. About a century later, Georges de Mestral developed an innovative fastening device, later named Velcro, after witnessing the attractive properties of the burr from a Burdock plant (Figure 2).

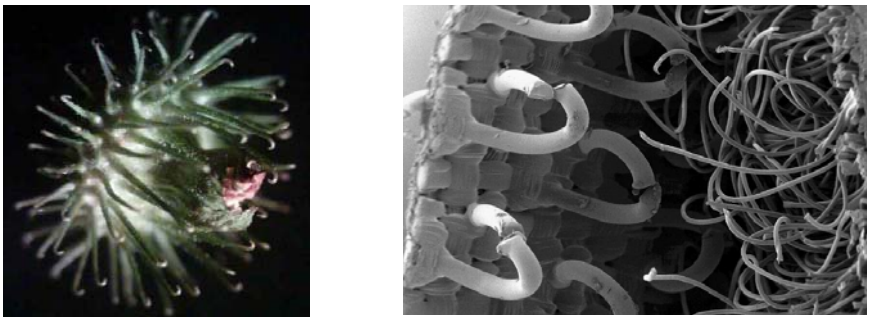


Figure 2: Burdock plant (left) [Matt03] and Velcro (right) [Ekst05]

Over the past few decades, the scope of bio-inspired design has diversified beyond aeronautics and architecture, to all fields of engineering. Engineers are now developing new materials, lifelike robotics, and many more innovative devices that are based on nature's solutions to similar problems. This growth in bio-inspired product development is only recent, as the technology has become more able to handle the complexity of

nature’s design and as engineers have become more aware of the wealth of possibilities that nature can provide.

1.2.2 Benefits

Nature offers engineers a blueprint of its designs that are highly effective, efficient, and adaptive. Nature has had millions of years to evolve and perfect its designs to solve specific problems and be best suited for a given environment. As a result, nature produces designs that are highly effective; they have been optimized to deliver high performance and functionality in their given environment. For example, biological materials such as wood or antler bone exhibit exceptional performance due to their material structure. Such effectiveness is also present in nature’s manufacturing processes, which are able to shape and assemble some materials far better than we currently do. As a result, nature produces structures that have multi-material design, geometrically complex interfaces, continuous material grading, massively parallel assemblies, and can achieve a high degree of articulation.

Nature’s designs are also highly efficient; they expend the least amount of energy and resources that are needed to survive. Additionally, nature is able to produce very diverse products from only a few common components, whereas we use a great number of materials and components to achieve new designs. Therefore, adapting ideas from nature to engineering solutions may result in more efficient and less costly products.

Nature is constantly changing. Animals and plants respond to their environment and often adapt their shape or structure to best suit the current conditions. Engineered products that could modify their geometry or orientation based on their environment would be useful in many applications. Additionally, engineers may be able to create materials and structures that evolve over time, constantly modifying their design. Such an idea may even extend to creating materials and structures that are able to design themselves.

1.3 Bio-inspired Product Development

To illustrate how looking to nature for design concepts can benefit product development, consider the following scenario. A team of engineers is working on the development of an autonomous underwater vehicle for the primary application of underwater mine reconnaissance. The engineers first identify the functional requirements that the vehicle must satisfy. These functions are the following:

- FR_1: Propel vehicle through water
    - $FR_{1.1}$: Acquire energy
    - $FR_{1.2}$: Convert energy into motion of vehicle
- FR_2: Maneuver vehicle through water
    - $FR_{2.1}$: Regulate depth of vehicle
    - $FR_{2.2}$: Regulate direction of vehicle
    - $FR_{2.3}$: Regulate velocity of vehicle
- FR_3: Carry payload
- FR_4: Detect location of mines
- FR_5: Send information

If the engineers were to search for design concepts over the engineering design space, then they would encounter existing engineered designs that meet the same functional requirements, such as a submarine or torpedo. These designs would provide candidate solutions that satisfy the functional requirements of their design task. For example, function FR_1, “Propel vehicle though water”, may be satisfied by the use of a propeller or thrusters. By searching for design concepts for each functional requirement from these existing products, a final design can then be generated. In this scenario, a typical final design would be a conventional Unmanned Underwater Vehicle (UUV), shown in Figure 3. While such a design offers many advantages, including high speed and long range, it has limited maneuverability which is required for avoiding underwater obstacles.

Figure 3: Unmanned Underwater Vehicle (UUV) [Publ04]

If the team of engineers were to take a different approach during concept generation and search over the biological design space, they would locate many examples of animals that satisfy the necessary functional requirements. One such example is the yellow-fin tuna, shown in Figure 4. The yellow-fin tuna is an optimal candidate for design concepts

because it is very streamlined and is highly maneuverable, able to accelerate quickly and change direction within a small turning radius.

Figure 4: Yellow-fin Tuna [Mara05]

By looking to nature's solution to the same functional requirements, the engineers are exposed to unique ways of solving design problems. For example, function FR_1, "Propel vehicle though water", is accomplished by the tuna by using body undulation to create vortices in the water. Such a concept wasn't considered as a means of propulsion for an underwater vehicle until 1993. By implementing this design concept along with many others inspired by the tuna, the final design is a bio-inspired underwater vehicle that looks and moves like the tuna. An example of this device is the Vorticity Control Unmanned Undersea Vehicle (VCUUV) built at Draper Laboratory (Figure 5) [Ande99].

Figure 5: Vorticity Control Unmanned Undersea Vehicle (VCUUV) [Ande99]

This vehicle mimics the morphology of the tuna with a low drag body, a flexible hull, and caudal and pectoral fins. Also, the VCUUV mimics the kinematics of the tuna by using body undulation for both propulsion and maneuvering. The result of this bio-inspired design is an underwater vehicle with improved maneuvering capabilities, able to make turns very quickly and in small spaces.

1.4 Challenges

The previous design scenario illustrated how including nature in the concept generation phase of product development can result in new and innovative designs that may offer improved performance. However, bio-inspired design concepts are often neglected in engineering product development. It is only recently that bio-inspired concepts have been implemented into a variety of products and started to gain attention. The reason for this slow growth is because of two challenges that must be overcome to enable engineers to discover the full potential of nature's designs.

The first challenge is to make engineers more aware of biological concepts and bio-inspired products. Currently, many engineers overlook solutions found in nature simply

because they do not know to look there. The second challenge is to make the existing knowledge and application of bio-inspired concepts easily accessible to engineers. Currently, most bio-inspired research takes place over a variety of fields and is conducted in highly specialized areas. Consequently, there is no one source where this information resides. In addition, in searching for bio-inspired concepts there is a different terminology that is used. Biological solutions are described in a different manner than is done in engineering. Therefore, an engineer searching for ideas in nature may return with poor results.

1.5 Proposed Solution

To assist engineers in searching nature for candidate solutions that can be applied to product development, we have developed a design tool that will locate bio-inspired concepts and be easy to use by both engineers and biologists. Such a tool should contain a repository that archives bio-inspired products and design concepts, allowing users to quickly and easily access this knowledge. In developing such a repository, there are several challenges. First, the archived information must make biological information accessible to engineers. Therefore, the repository of products and concepts must include detailed information regarding the biological source of inspiration, as well as the applications of such concepts.

Secondly, engineers often generate design concepts to satisfy a set of functional requirements. Therefore, a repository of bio-inspired product concepts must capture the functionality of the products and concepts being recorded. Furthermore, the archived

functions may be describing the functionality of a product or a biological system, which engineers and biologists often describe in very different terminology. Therefore, a functional language is needed that uses common terms and is capable of archiving the functions of any system, including any engineered product, bio-inspired product, or biological system. This method of archiving functions must ensure the expressiveness and completeness of the functions being recorded, while remaining easy to use for both biologists and engineers. Also, to ensure the success of this language, it must be extensible. Furthermore, an evaluation of this method that directly compares it to a current alternative is necessary in order to demonstrate its advantages.

A third challenge is the retrieval of information from the repository. In order to make this information easily accessible, the repository must support a content-based search by which one can quickly retrieve products or concepts that satisfy certain functions. Therefore, intuitive and flexible search tools are needed to allow users to navigate and retrieve design concepts. Lastly, the success of such a repository of information depends upon the amount of knowledge it contains. Therefore, the repository must be open for engineers and biologists to add their new designs and biological discoveries. Figure 6 illustrates the general process of archiving and retrieving design concepts that will be implemented in the proposed solution. Both the product information and biological information will be archived into the repository, along with the functions of either the bio-inspired product or biological system. In order to retrieve these design concepts from the repository, the information must be able to be searched by keyword as well as function.

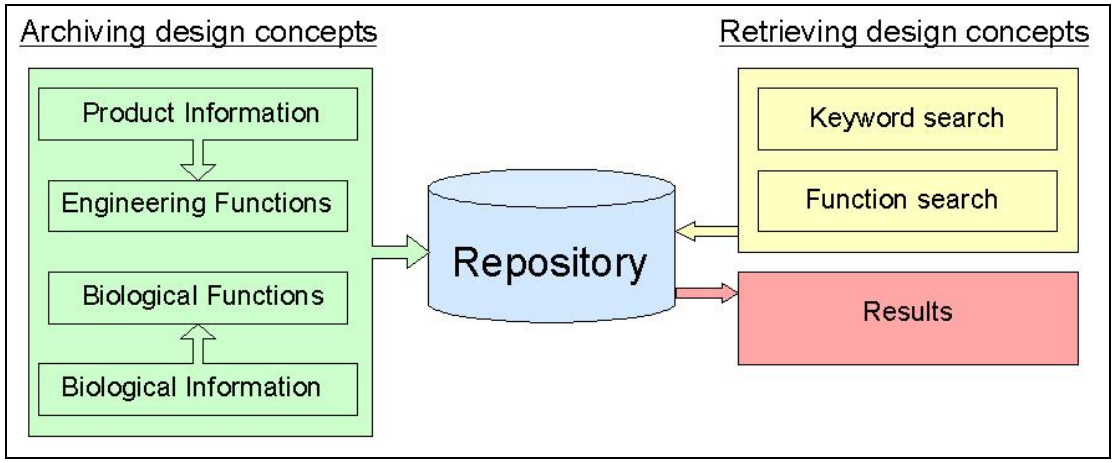


Figure 6: Archiving and retrieving design concepts

1.6 Outline of Thesis

This thesis will describe the development of a design tool that meets these challenges. First, related work will be discussed and the advantages and disadvantages of various approaches will be noted. The next chapter will introduce the approach and techniques that were used to develop the complete design tool for the archival and retrieval of bio-inspired products and concepts. The development of this system is composed of the following three elements:

1. Repository of bio-inspired products and concepts
2. Functional Description Template
3. Search tools

The repository of bio-inspired products and concepts that has been developed will collect a variety of bio-inspired research into one place and record the functions of the entries to provide engineers with candidate solutions to design problems. The contents of the

repository and the various forms of data entry will be introduced. Next, the development of the Functional Description Template, which allows users more freedom to express the functionality of design concepts, will be described along with a detailed discussion of the terminology and usage of the method. Additionally, a study that was conducted will offer a direct comparison between the Functional Description Template and an alternative method, a Functional Basis. Lastly, different content-based search methods will be proposed that allow the user to easily navigate and retrieve design concepts from the repository.

Chapter 2: Related Work

There has been much work done in bio-inspired design as well as the development of databases and functional languages for archiving and retrieving these design concepts. However, due to space restrictions, it is not possible to include a comprehensive literature review of these fields. Instead, brief descriptions will be provided on the main topics related to this work and references to survey papers and representative works will be cited. This chapter will elaborate on the following topics as they relate to the process of archiving and retrieving design concepts that was shown in Figure 6.

1. Bio-inspired design concepts
2. TRIZ: Retrieving engineering design concepts
3. Biological Effects Database: Archiving biological design concepts
4. Biological Functions: Archiving biological functions
5. Functional Basis: Archiving engineering functions
6. Natural Language Analysis: Searching by function

2.1 Bio-inspired design concepts

Bio-inspired engineering has recently become a rich field with many specialties. The variety of specialized work that is being done is of great value to engineers and a critical part in building a large repository of bio-inspired design concepts. This varied work includes such topics as bio-inspired design, materials, actuators, sensors, and robotics. Bio-inspired design includes research on the designs found in nature that may offer ideas to engineers [Ball01, Beny02, Matt98, Voge00, Voge03]. Research on bio-inspired materials includes work on developing new materials inspired from such living entities as

mollusk shells, nacre, and spider silk [Kapl98, McKi02, Sari95, Sell98, Wang94]. Bio-inspired actuators are being developed that mimic natural muscle [Cohe98, Cohe01, Korn95, Shah94]. Bio-inspired sensors seek to take advantage of the impressive sensing capabilities found in nature to develop such sensors as flow sensors and strain sensors [Fan02, Kuc97, Skor02, Toko00]. Lastly, many bio-inspired robots are being developed that mimic the locomotion of a variety of animals, from cockroaches to flies [Ayer02, Clar01, Cohe03, Elli99]. From this vast amount of research, there are many potential bio-inspired design concepts that can be archived.

2.2 TRIZ: Retrieving engineering design concepts

TRIZ is an acronym for Teoriya Resheniya Izobreatatelskikh Zadatch, which translates to Theory of Inventive Problem Solving. TRIZ was created in 1946 by Genrich Altshuler, a Russian engineer and scientist, who sought to systematically describe the invention of products and devices [Alts84]. His theory of invention was that engineering designs use repeated key principles that may be studied and then archived. These principles could later be retrieved and applied to future design problems. From this idea, he developed several problem-solving methods based upon the study of over 1.5 million patents. One of these methods, the contradiction matrix, relates to the work presented in this thesis in that it is used to retrieve design principles that have been previously archived. This matrix is used to identify a contradiction between any of 39 engineering parameters and then list, from 40 principles of invention, which ideas may resolve the contradiction [Alts98].

While the contradiction matrix retrieves design concepts to aid in solving design problems, it does so in a different manner than that proposed in this thesis. The repository of bio-inspired products is intended to allow users to retrieve design concepts based upon a functional requirement. Consider, for example, the problem of designing a mobile robot, where one functional requirement may be to detect mines, as was the case for the VCUUV. The contradiction matrix requires this design problem to be reformed into the contradiction between two engineering parameters by first identifying a desirable parameter and a contradictory undesirable parameter. For this example, the most applicable contradiction is that between the 28th parameter, "Measurement accuracy" and the 37th parameter, "Difficulty of measuring". Rather than searching for candidate solutions that meet the specified functional requirement, the contradiction matrix will provide several key principles that may be applied to overcome the stated contradiction. This process is illustrated in Figure 7.

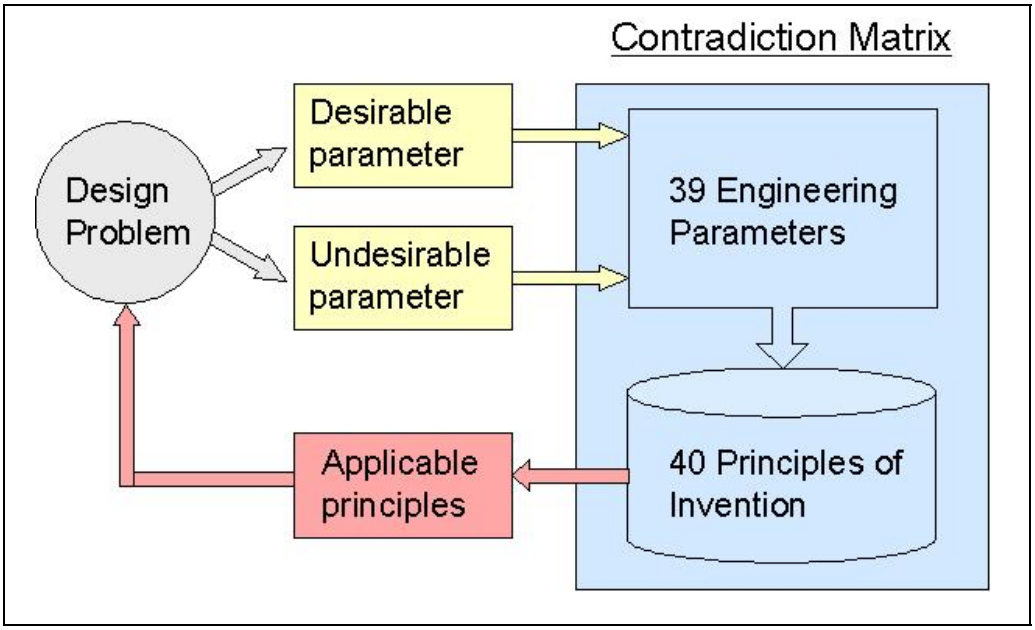


Figure 7: TRIZ: Contradiction Matrix

Although taking a different approach, the contradiction matrix used in TRIZ provides engineers with very useful information and has been used successfully to yield applicable design concepts. However, allowing the retrieval of key principles or existing products based upon functional requirements would also be of value to engineers. Therefore, the work presented here has the potential to be used in conjunction with the contradiction matrix and other methods used in TRIZ. The products and concepts that are archived in the repository may provide useful bio-inspired examples of the principles that solve the contradictions. In fact, work is currently being done at the Center for Biomimetic and Natural Technologies at the University of Bath to integrate biology into TRIZ [Vinc00, Vinc02]. Their work aims to make biomimetic design concepts available in TRIZ by updating the contradiction matrix. The repository described in this thesis may provide examples of biomimetic design for the updated contradiction matrix and can offer an important update to the wealth of knowledge available through TRIZ.

2.3 Biological Effects Database: Archiving biological design concepts

The Center for Biomimetic and Natural Technologies at the University of Bath is also developing a database of biological effects to make biological information available to engineers [Boga02, Boga03]. A biological effect is the result of a function of a biological system. The database will include many fields of information about the biological system, including the following:

- Name of biological system
- Description

- Function
- Level of organization
- Medium
- System/Media interactions
- Cause and effect characteristics
- References

This information is archived into the database using an online form that requires different types of data entry for the different fields. Some fields, such as the name of the biological system or the description, are to be recorded using freeform text entry, as shown in Figure 8. The user is able to freely type in any information in the spaces provided.

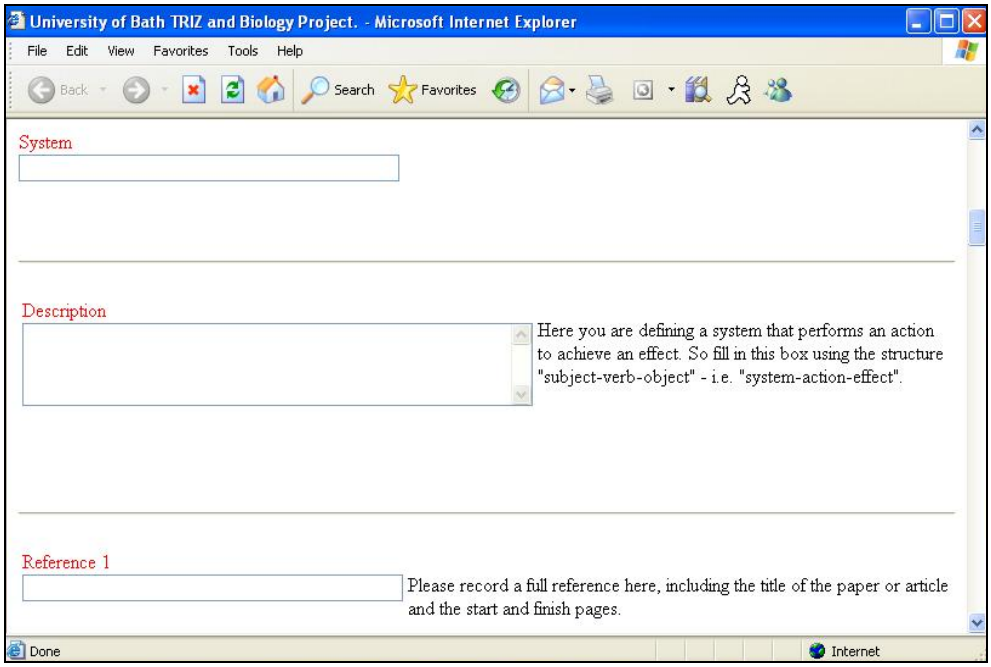


Figure 8: Biological Effects Database: Freeform text entry [Boga03]

For other fields, such as level of organization or medium, the user must select a description from a list of available choices, as shown in Figure 9.

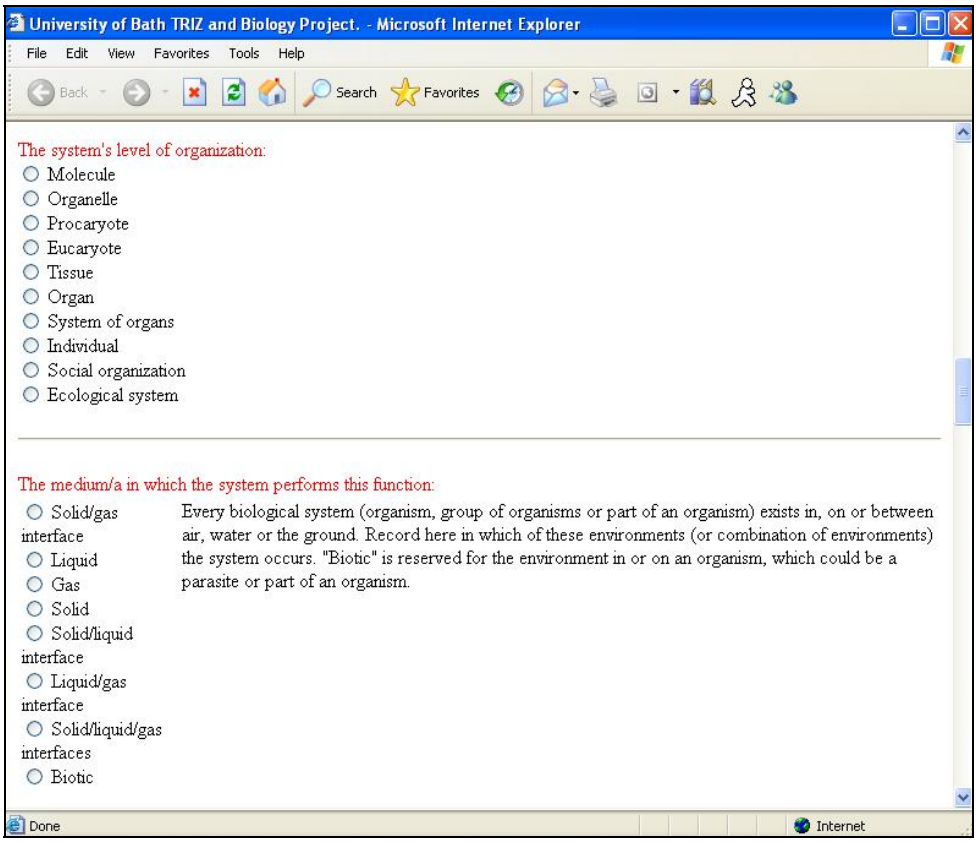


Figure 9: Biological Effects Database: Menu selection [Boga03]

The archived information can then be searched by completing an online search form that is very similar to the data entry form. The fields that contain text entered by the user are searched for any search terms that were entered. The fields that contain a selected option are searched for matches to the option selected by the user conducting the search.

The biological effects database provides a wealth of information on biological systems and is able to make bio-inspired concepts more accessible to engineers by recording the

functionality of these biological systems. However, a useful extension of this database would be examples of engineered products that were inspired by these biological systems or potential applications. It is this need that the repository of bio-inspired product concepts seeks to fulfill. The biological information that is archived in this database can be incorporated into the repository of bio-inspired product concepts and linked to engineered products and devices that were inspired by biological systems.

2.4 Biological Functions: Archiving biological functions

Since the repository being described in this thesis seeks to record the functionality of both products and bio-inspired concepts, it is valuable to examine how the biological effects database records functions. The function entry in the database is a biological function that is chosen from an "engineering friendly" classification of possible functions shown in Figure 10. This classification provides 6 high-level "program functions" that contain beneath them a total of 271 more specific functions. Using these terms, one should be able to describe the function of any biological system.

Create				
Reproduce	***Produce***	***Grow***	***Deposit***	***Make tools***
Multiply, Imitate, copy, etc	Increase, emit, generate, etc.	Increase, assemble, accumulate, etc.	Increase, store, save, etc.	Use nature, modify nature, design, etc.

Preserve						
Defend	***Regulate temperature***	***Insolate***	***Osmose***	***Respire***	***Feed***	***Support***
Clean, protect, resist, seal, etc	Heat, cool, freeze, readjust, etc	Lighten, darken, ignite, etc.	Wet, dry, drink, etc.	Breathe, ventilate, stabilize, etc.	Nourish, deposit, etc.	Hold, border, etc

Destroy		
Feed	***Defend***	***Destruct***
Capture, graze, ingest, digest, shred, chop, etc.	Stop, beat, attack, etc.	Decrease, bend, crack, corrode, erode, etc.

Convert	
Change phase	***Transform***
Melt, freeze, evaporate, crystallize, etc.	Embed/absorb, extract/separate, metamorphose, etc.

Move			
Transport	***Migrate***	***Locomote***	***Manipulate***
Conduct, distribute, deliver, transfer, etc.		Roll/traverse, vibrate, adapt, fly, burrow, etc.	Lift, drop, orient, rotate, etc.

Regulate		
Inform	***React***	***Control***
Sense, detect, locate, etc	Select, behave, response, etc	Sense, detect, measure, etc.

Figure 10: Biological Functions [Boga03]

The above functions offer an organized and complete description of biological systems. However, the repository of bio-inspired product concepts will archive the functionality of both engineered products and biological systems. Therefore, a more complete and

universal functional language is required. Some of the necessary features of this language can be observed by studying these biological functions.

The above classification of terms may be “engineering friendly”, however many of the terms themselves are biology specific, such as “grow” and “nourish”. If biology and engineering are to be described in the repository, more general terms must be used. For example, “increase” implies the same function as “grow” but is a more general term. Also, rather than provide objects for the functions to act on, many of the terms are noun specific, a reason why so many terms are needed. For example, the function “drink” implies that a liquid is being taken in, whereas the term “ingest” or “take in” would be more general. If the noun that the function acts on could be described separately, more potentially useful information could be stored. Finally, the classification of the functions makes use of a hierarchy that may not be intuitive to some users and requires a specific line of thought to arrive at the desired function. For example, if a user wishes to locate the function “drink”, they must first identify the program function as “preserve” and then the goal function as “osmose” before the term “drink” can be found. While this hierarchy does provide an organized way to represent the information, it may mask the desired terms from users that are not familiar with the specific hierarchical structure that is used. By incorporating these modifications into the development of a more general functional language, a method of archiving functions can be developed that applies to both biology and engineering and is easy to use.

2.5 Functional Basis: Archiving engineering functions

Currently, many methods exist for archiving engineering functions. One of the most commonly used methods is a functional basis, which is a taxonomy of terms for standardizing descriptions of function and flow. A functional requirement is formed by combining a function term and a flow term. The function term acts as the verb and the flow term as the noun. These terms are presented to the user in a hierarchy. Many approaches have been made in developing a functional basis; however, several of these efforts have been reconciled into a single functional basis under work being done at the University of Missouri Rolla [Hirt02]. This functional basis contains function terms in a 3-level hierarchy, with the highest level containing 8 functions. The flow terms are also organized into a 3-level hierarchy, and the highest level contains three terms – material, signal, and energy.

There are many benefits to using a functional basis to describe product functions. If users were to record functions using their own words rather than a functional basis, the same function could appear in any number of ways. The use of a functional basis reduces this variability and provides uniformity in the archived functions. Also, many words that may be used in functional descriptions can have multiple meanings. By providing a fixed set of terms, each with a definition and example of usage, a functional basis reduces any ambiguity in the terms that are used. Lastly, a functional basis facilitates the retrieval of functional information by requiring the functions to be archived using standardized terms.

Due to the advantages mentioned above, a functional basis appears to be an effective way to archive functions into the repository. However, in order to offer many of the advantages in retrieving functions, a functional basis requires some limitations in archiving functions. One limitation is the loss of information by requiring selection from a fixed set of terms. Although this method allows for efficient retrieval, it limits the user's expressiveness and completeness in archiving functions. By requiring the user to select from a given list of terms, the user's desired terminology must often be changed. This terminology could be very useful in locating products by keywords that appear in the functional description. Also, the user may have to select a term that does not accurately represent the intended meaning of the functional statement. Information is also lost by requiring the user to form functional statements in simple verb-noun sentences. In everyday speech, users may describe the functions of products in more complex sentences that contain additional information, such as information regarding the properties of a flow or additional prepositional phrases. A second limitation of a functional basis is that the arrangement of terms into a hierarchy may be non-intuitive to an occasional user. As described for the functions in the biological effects database, a hierarchy of functions does offer a clear and organized way to represent numerous terms. However, each user may have a different way of thinking of functions hierarchically. Therefore, it is difficult to implement a hierarchy that will be intuitive for all users and may potentially make certain terms difficult to locate. For example, consider the function "detect mines". The function term "detect" can only be located by first looking to the primary term "signal" and then the secondary term "sense", before "detect" is found to be an available tertiary term.

The benefits in retrieving functional information make a functional basis an ideal starting point for developing a method for archiving and retrieving functions into the repository of bio-inspired products and concepts. By making some modifications to this method in the areas mentioned above, the quality of the archived functional information may be improved.

2.6 Natural Language Analysis: Searching by function

The final piece of related work is a natural language analysis for biomimetic design that is being developed at the University of Toronto [Chiu04, Mak04]. This method directly searches biological knowledge that is already available in natural language, such as published biology texts. Currently, the biology text “Life, the Science of Biology” is being used in the development of this method. The natural language analysis searches the text by function using a combination of human and computational processing. The search is designed to identify dominant biological themes that may provide design concepts to satisfy the function being searched. To make the function search more flexible, this natural language analysis uses WordNet [Mill03] to generate alternative function keywords. WordNet is an electronic database of words based upon how humans remember language. For the function term that is being searched, WordNet provides many troponyms as alternative search terms. A troponyms is a verb that expresses a specific manner of another verb. For example, the verb “march” is a troponym of “walk” because marching is one way of walking. The complete process used to search a text includes the following steps:

1. Identify keywords
2. Search text for keywords
3. Remove unlikely relevant matches
4. Find frequently co-occurring words
5. Analyze results

To demonstrate this process, consider a search for biological inspiration to meet the function “to clean”. The user would first identify a function keyword to search, which in this case would be “remove” since cleaning requires the removal of dirt or other substances. WordNet would then generate 179 troponyms of “remove” to act as alternative search terms. The text is then searched for these terms and any unlikely relevant matches are removed. 38 relevant matches remain, with the troponyms “kill” and “eliminate” appearing the most frequently, which may be expected in a biology text. Next, the search finds the most frequently co-occurring words of these troponyms. These words, which come before or after the matched troponyms, are the agent (what is performing the function) or object (what the function is acting on) of the function keyword. From the co-occurring words in this search, the most common agent was found to be “predators” and the most common objects were “species” and “prey”. By analyzing the overlap of frequently occurring function keywords with the agents and objects that are present, a dominant biological theme can be identified. The dominant biological theme for the function “remove” is identified to be “species interaction through competition (for resources) and predator and prey relationships.” This result can then offer bio-inspiration for design concepts for cleaning. One such bio-inspired solution is to

"use a less porous surface that provides fewer locations (resources) for dirt to settle." This complete process is illustrated in Figure 11.

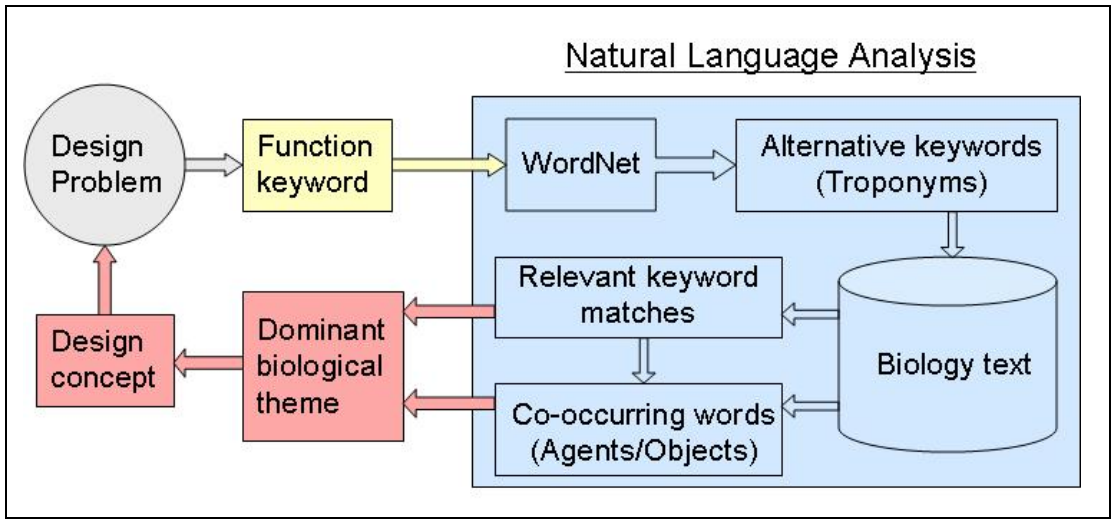


Figure 11: Natural Language Analysis

This natural language analysis is an appealing approach because it can search existing texts and requires minimal input by the user. Also, the use of WordNet to provide alternative function keywords allows for a more flexible search of the material. However, the results of this search require much analysis to identify the relevant information. Applying some of the concepts used in this natural language analysis to the repository of bio-inspired product concepts may allow for more effective retrieval of functional information. As previously described, retrieving functional information that is not archived using a fixed language, like a functional basis, can be very difficult. However, if a search could be conducted for words that are similar to those specified by the user, such as troponyms, then the results may provide solutions that meet functions with the same meaning but use different terms.

2.7 Summary

With respect to the proposed solution presented earlier, much can be learned from the related work presented above. First, in developing a repository of bio-inspired products and concepts, it is important to include information about the biological systems, as seen in the biological effects database, while also presenting information on product development that will aid engineers. When creating a functional language to access this information, a functional basis has proven to aid in archiving and retrieving the information. However, it is also important to allow the user freedom to express the functions in terms of language and sentence structure. This capability will allow for more expressive and complete functional descriptions that retain the user's intended meaning. Whatever terms are used should be common language terms and not arranged in a possibly confusing hierarchy. The natural language analysis has also shown that by searching for many alternatives to a single function term, many useful results may be found. Lastly, as seen in all of the related work, easy to use and flexible search tools are required to locate meaningful results.

Chapter 3: Bio-inspired Products and Concepts Repository

Based upon the proposed solution and the lessons learned from examining the related work, a complete system was developed to make bio-inspired design concepts more accessible to engineers. This system, illustrated in Figure 12, contains the following three main parts:

- Repository of bio-inspired products and concepts
- Functional Description Template
- Search tools

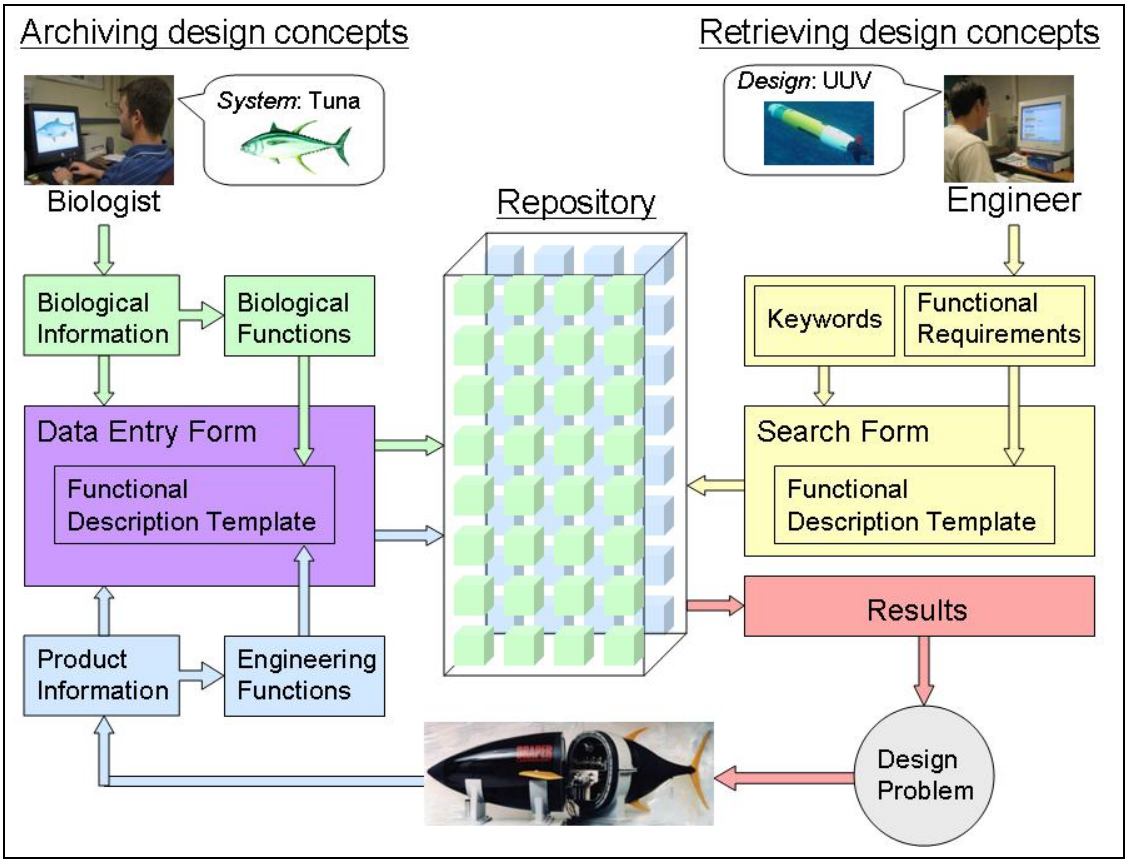


Figure 12: System Overview

This system can be used to archive both biological systems that may offer inspiration for future designs, as well as the engineered products that result from such inspiration. In order to archive a product or concept into the repository, the user must fill out the data entry form and use the Functional Description Template to record the functions. As shown in Figure 12, a biologist is archiving the biological information and functions for the tuna into the repository. A user may then use the search form to retrieve design concepts from the repository based upon a keyword or function. Functions can be searched by entering a function into the Functional Description Template in the search form. The products or concepts that are returned in the search can then be applied to the design problem to create a new bio-inspired design. In Figure 12, an engineer is seeking design concepts for designing an Unmanned Underwater Vehicle (UUV) and may retrieve design concepts based upon the tuna that are archived in the repository. These design concepts can then be applied to the design problem and may result in the development of a new bio-inspired product. This product can then be archived into the repository using the data entry form and Functional Description Template. The Functional Description Template is able to represent both biological and engineered functions in a common language and will be described in Chapter 4. In following sections will describe the repository and the entry of information.

3.1 Contents of the Repository

The repository being developed archives bio-inspired products and concepts. Bio-inspired products refer to products in any stage of development that have taken inspiration from nature. These products may be anything from a new material to a complex mechanical

device; they do not necessarily have to be consumer products and can be any type of device. A bio-inspired concept refers to an observation of some function being met in nature. This concept need not be implemented into a product yet. Such concepts may be archived into the repository and any potential applications may be recorded. Currently, the repository contains 89 records of bio-inspired products, which are provided in Appendix A. These products were identified and researched though a search of journal papers, conference papers, magazine articles, and websites that discuss current bio-inspired research. The searches that were conducted explored bio-inspired actuators, sensors, materials, robots, and various other mechanical devices and consumer products that were inspired by nature. All of the products that were located were then recorded into the repository. For each entry, the following sets of fields are recorded.

- Product Information
    - Product name
    - Product type
    - Product description
    - Development stage
    - Applications
- Biological Inspiration
    - Biological name
    - Biological type
    - Biological description
- Functions
- Resources

- Primary source
- Additional references
- Media

For a bio-inspired product, all of the above fields may be populated. If a bio-inspired concept is being archived, the product information fields will remain empty, expect possibly the applications field. The functions of the product or in the case of a concept, the functions of the biological system, require many fields to be populated by using the Functional Description Template. The information that is recorded with this template is described in Chapter 4.

3.2 Data Entry

For the bio-inspired product repository to grow and become more useful to engineers, users of the repository must be able to submit entries of new products or concepts. If the repository were to be populated by a single person or group, it would take a long time for the repository to grow and some research may be overlooked.

To make entering information into the repository accessible to all users, a web-based form was created, which is shown in Figure 13. This form allows a user to quickly and easily enter information into all the appropriate fields. Upon submission, the entered information is placed in the corresponding fields in the repository and is then available to all users. When using the data entry form, there are three distinct types of data entry:

- Freeform text entry
- Menu selection
- Functional Description Template

Each field on the data entry form and, hence, each field in the repository is completed by using one of these three methods. The method of data entry that is required for each field was chosen to best accommodate the type of information being recorded and to ensure that the form is easy to use.

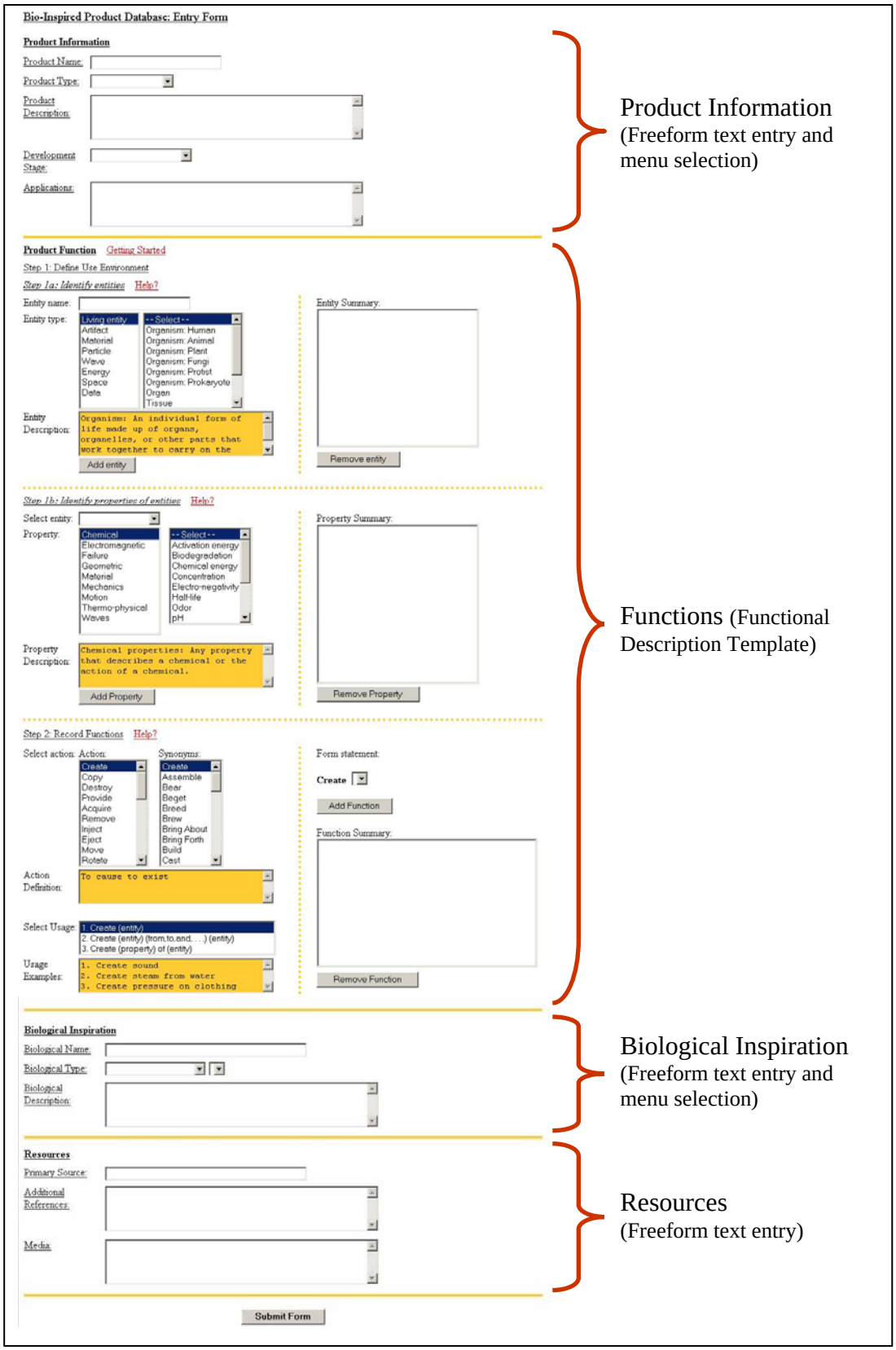


Figure 13: Data Entry Form (without scrolling)

3.2.1 Freeform text entry

The most prevalent method of data entry is freeform text entry. For any field that uses this method, the users simply type in the requested information in their own words. The fields that use this method are shown in bold:

- Product Information
    - **Product name**
    - Product type
    - **Product description**
    - Development stage
    - **Applications**
- Biological Inspiration
    - **Biological name**
    - Biological type
    - **Biological description**
- Functions
- Resources
    - **Primary source**
    - **Additional references**
    - **Media**

By allowing freeform text entry for these fields, the users are able to record the requested information in their own terminology, rather than being forced to use a term that may not be as descriptive. Also, for such fields as “Biological Description” or “Product

Description", freeform text entry allows the users to enter their description in complete sentences. By allowing the user to provide lengthy descriptions of the product or biological inspiration, more terms will be used that will aid in retrieving the entry during a keyword search. For the final three fields, "Primary source", "Additional references", and "Media", users may type in a website address to link to a document file, a picture, or video file. Figure 14 illustrates the freeform text entry for the Product information and Figure 15 illustrates the entries for the Biological inspiration and Resources.

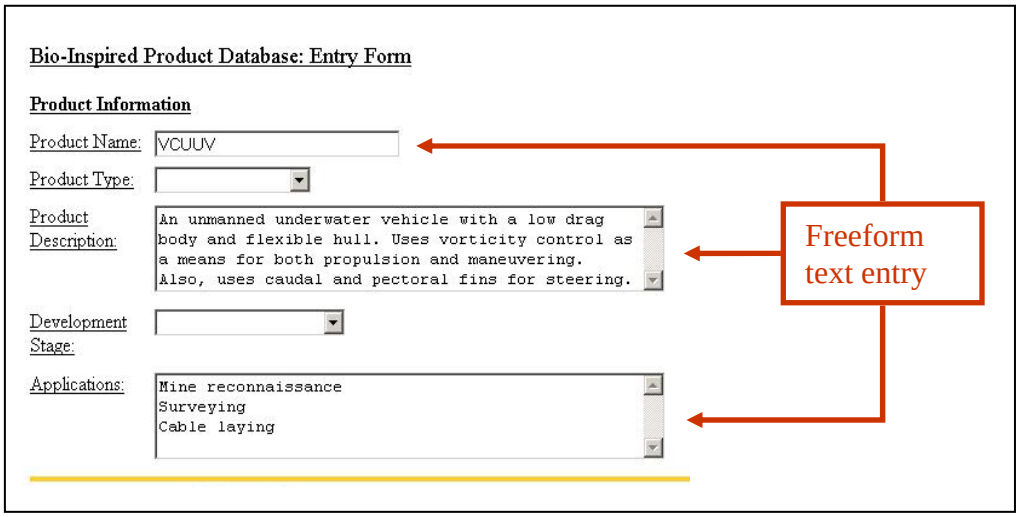


Figure 14: Freeform Text Entry – Product Information

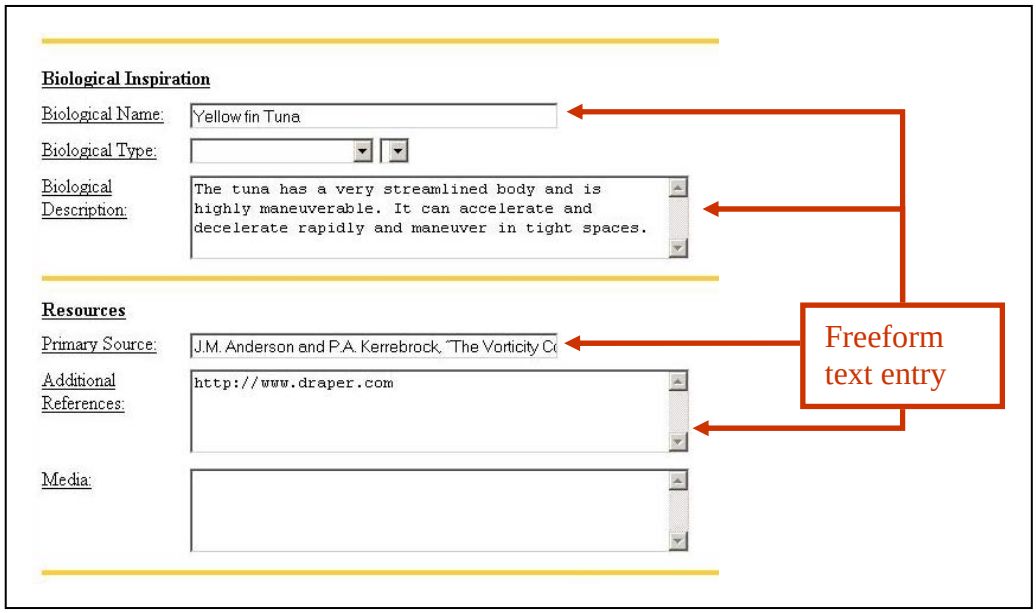


Figure 15: Freeform Text Entry - Biological Inspiration and Resources

3.2.2 Menu selection

Another method that is used for data entry is menu selection. This method requires the user to make a single selection from a drop-down menu of available options. This method of data entry applies to the following three fields in the repository, shown in bold:

- Product Information
  - Product name
  - **Product type**
  - Product description
  - **Development stage**
  - Applications
- Biological Inspiration
  - Biological name
  - **Biological type**

    - Biological description
- Functions
- Resources
    - Primary source
    - Additional references
    - Media

“Product Type” refers to the classification of a product into a category of products from a provided list. A product can be classified as one of the following types:

- Material
- Structure
- Actuator
- Sensor
- Robot
- Other mechanism
- Algorithm

This field was included as a compliment to the “Product description” field. In the “Product description” field, the user may type in a lengthy description of the product which can later be searched by keyword. However, providing a classification of the recorded product from a fixed set of choices offers the additional feature of browsing products by their classification, or even filtering a search by the product type. The available options for this classification were chosen by reviewing several mechanical

products, including the 89 products that are currently in the repository. Categories were created that were neither overly specific nor too general. Currently, the available options reflect classifications of mechanical devices. If the scope of the repository is expanded in the future, other options may need to be added. The classification by product type of the 89 bio-inspired products that have been archived into the repository can be seen in Appendix A1.

The next field that requires menu selection, “Development Stage”, refers to the current stage of development of a bio-inspired product. This selection is made from the following four predetermined stages of product development:

- Biological research
- Concept development
- Product development
- Product available

This field also allows additional information regarding the product’s description to be entered. As with the “Product type” field, this field offers the benefit of browsing or filtering products based upon their development stage. The information in this field is chosen from a provided list of options because users may describe the same stage of product development in different ways. The four available options were chosen because they represent very distinct stages of development. “Biological research” refers to an entry for which the bio-inspiration is still being explored. Such an entry may be a biological system that offers some unique advantage to engineers or perhaps a product

that has yet to be explored but may be possible due to some bio-inspiration. “Concept development” refers to a bio-inspired product that is in the early stages of product development, where the conceptual workings of the product are being developed. “Product development” refers to a product that is in the later stages of the development process where final design issues are being resolved and prototypes are being constructed and tested. “Product available” refers to a product that has been completely designed and produced and is now commercially available. Shown in Figure 16 is the menu selection for the two fields mentioned above.

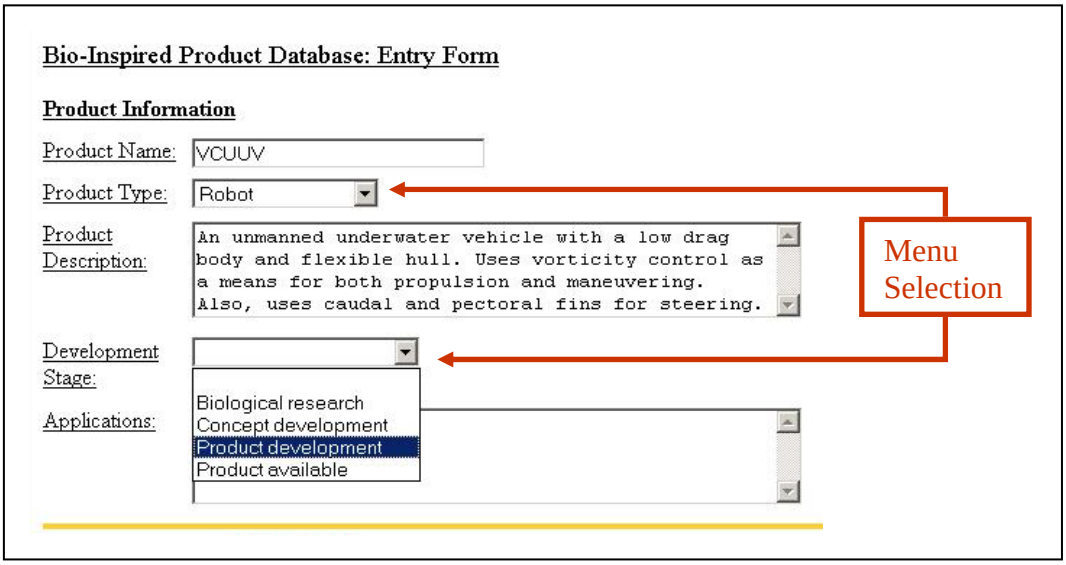


Figure 16: Menu Selection - Product Information

The last field that is entered through menu selection is “Biological type”, which refers to the classification of the biological source of inspiration in a given taxonomy. This field allows the user to provide additional information regarding the biological source of inspiration. While the biological name can be entered through freeform text entry, the classification of this biological system allows similar sources of inspiration to be related

in the repository. Therefore, future searches may browse or filter products inspired by similar sources.

In order to provide a list of options in which to classify a biological system, existing biological taxonomies were consulted. However, these taxonomies are very detailed with many levels in the hierarchy. For this application, a more simplified version was desired. In order to limit the number of selections, the classification was reduced to a two-level taxonomy. In most classifications of biological organisms, there are five kingdoms – Monera (Prokaryotes), Protista, Animalia, Fungi, and Plantae. However, the majority of biological inspired products have been inspired by the animal kingdom and the animal kingdom is the largest and most diverse kingdom with over one million species. Therefore, the classification of "Biological Type" had to offer more available options for the animal kingdom, while still remaining a two-level taxonomy. Also, in order to make the biological classification more accessible to engineers, some of the biological terminology has been replaced with everyday terms. With these considerations, the following taxonomy was created:

- Animal (Vertebrates)
    - Human
    - Mammal
    - Bird
    - Fish
    - Amphibian
    - Reptile

- Animal (Invertebrates)
    - Insects, spiders, and crustaceans
    - Worms
    - Jellyfish, sea anemones, and corals
    - Mollusks
    - Sponges
    - Other
- Other organism
    - Plant
    - Fungi
    - Protist
    - Prokaryote
- Biological component
    - Organ
    - Tissue
    - Cell
    - Organelle
    - Virus
    - Protein
    - Other

Shown in Figure 17 is the menu selection for Biological Type.

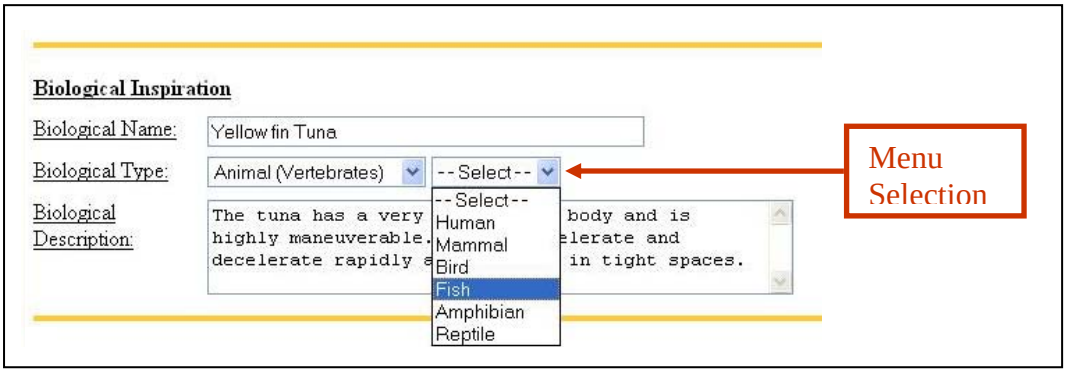


Figure 17: Menu Selection - Biological Inspiration

The biological type selected for the 89 bio-inspired products that have been archived into the repository can be seen in Appendix A1.

For all three fields that require menu selection, the selection from a fixed set of choices allows for the entry of additional information that can be efficiently archived and retrieved. By placing all products or biological systems into a single category for each field, the archived information can be quickly and easily browsed by other users.

3.2.3 Approach to recording functions

The third method of data entry is used to enter the functions of a bio-inspired product or a biological system into the repository. This method makes use of the Functional Description Template, which will be described in Chapter 4. The reason for developing this method is that a new approach to record functions is needed. The two previously described methods, freeform text entry and menu selection, are not by themselves best suited for recording functional descriptions.

Consider the use of freeform text entry. This method, while being straightforward and easy to use, is not optimal for searching fields that include very few terms. A keyword search of the “Product Description” field, for example, may provide very good results because the user is likely to enter many terms in describing the product. If lengthy descriptions are recorded, more words are included that would be common to searches for such a product. However, functional descriptions are usually very brief, and use a minimal number of terms to convey the functions of a product. If freeform text entry were to be used to record product functions, the functional descriptions could use any number of possible terms to convey the same meaning. For example, consider a function that is entered into the repository as “to contain water.” Now, consider a different user that wishes to search the repository for products that perform such a function. This user may search for this function using completely different terms, such as “to hold liquid” or “to store fluid” and would not be able to locate the desired product. Another difficulty with the use of freeform text entry for entering product functions is that the user may use technical terminology that may not be known to other users searching the repository and again, the products with such descriptions could not be easily located. Therefore, freeform text entry is clearly not best suited for recording product functions.

Now consider the use of menu selection to record product functions. Such a method would likely make use of a functional basis and provide the user with menus to select the desired terms. These terms, as described in a functional basis, would be a function term and flow term, each with a distinct menu. While this approach offers some benefits in

retrieving functional information, there are some limitations in the archival of the product functions. First, the use of a functional basis may be difficult for the occasional user due to the multitude of terms and their arrangement into a hierarchy. A functional basis contains many action terms that describe the function that a product may perform and arranges these terms into a hierarchy, beginning with a small set of high-level terms and expanding into many sublevels of more specific terms. A hierarchy may offer a concise and organized representation of several terms; however it is difficult to present a single hierarchy that will be intuitive for all users. A hierarchical structure that is foreign to the user expects that they follow a specific line of reasoning to arrive at the desired term stemming from its high-level term. However, some users may have difficulty locating the desired term. The second limitation with using a functional basis is that some information is lost when archiving functions. The user's expressiveness and completeness in recording a product's function are limited. The user is required to select terms that may be different from those expressed in the original functional description. Also, a functional basis only uses two terms to describe a function – the function term and the flow term. This construction forms a functional statement in a simple verb-noun sentence that may omit useful information. It would be beneficial for the user to describe the functions of a product using more complete sentences that can include compound arguments and prepositional phrases to more accurately describe the function.

While the use of a functional basis through menu selection has some limitations, there are benefits to using such a method. By limiting the user to a fixed set of terms, retrieval of information from the repository based upon function is simplified. As explained with

respect to freeform text entry, searching the repository by function is complicated by numerous possible terms being used. However, through menu selection, a fixed set of terms is available, each with a unique definition. Therefore, there is no ambiguity in searching for products by its intended function.

Freeform text entry or menu selection offered alone is not best suited to record the functions of a product. For this reason, the Functional Description Template was developed to combine the strengths of each of the above methods. The desired benefits from freeform text entry are a data entry method that is intuitive and easy to use, and provides more freedom to the user to enter complete functional descriptions in their own words. The benefits of menu selection from a functional basis that are desired are the efficient archival and retrieval of the product functions and the well defined semantics of any terms being used. In the next chapter, the Functional Description Template will be described in detail and shown to offer these advantages.

Chapter 4: Functional Description Template

In order to develop an easy to use and expressive method for recording functions, it was necessary to first understand how people naturally express a functional statement. To accomplish this, an informal study was done asking people to write down the functions of common products. From these results, it was clear that there was no uniform way to represent a function. Some functions were very brief statements, while others were lengthy descriptions. However, all the functional statements used the same elements to form a sentence (verbs, nouns, etc.). Therefore, if common arrangements of these terms could be identified, then standardized templates could be provided for users and then the desired terms could be entered.

This concept is the basis for the Functional Description Template, a new method for recording product functions that provides a predetermined sentence structure as a template to allow the user to form more complete functional descriptions. The methods of data entry used to fill in the template are a combination of freeform text entry and menu selection, which allow the recorded information to be efficiently archived and retrieved while ensuring that the system is easy to use by both engineers and biologists. This method of recording functions is applicable to all systems, including conventional engineered products, bio-inspired products, and biological systems.

4.1 Elements of a Functional Statement

To identify useful and common templates, the elements of functional statements needed to be studied. Also, such information may be used to determine the best means of

recording each element in the template. The different elements in a functional statement are simply the different parts of speech that may be used. These elements include the following:

- Verbs
- Nouns
- Adjectives and adverbs
- Prepositions, conjunctions, and articles

A functional statement usually contains one verb, which corresponds to the function term in a functional basis and here will be referred to as the action term. This term indicates what action is being performed. Nouns, on the other hand, have two main uses in a functional description. Primarily, nouns are used to indicate the entity on which the action term is operating. For example, in the functional statement “contain water”, “water” is the noun and is the entity that is being acted on by the verb “contain”. The water is what is being contained. The other use of nouns is to describe the property of an entity. For example, consider the function “increase velocity of water”. In this functional statement, “velocity” is the noun being acted upon by the function “increase”. However, “velocity” is not considered to be the entity that is being acted on, rather it is the water. “Velocity” is a property of the water and by performing some function on the velocity the water is therefore acted upon. From this example, it can be seen that nouns are used to describe either an entity or a property of an entity. Adjectives and adverbs are often used in functional statements to further describe an entity or to describe the manner in which an action is performed. For example, the functions “contain viscous fluid” and “quickly

increase velocity of water" use an adjective and adverb respectively to add detail to the functional statement. Lastly, prepositions, conjunctions, and articles are used to connect the previously described elements of the functional statement.

Based upon this information, the Functional Description Template will make use of the following three primary terms:

- Entity terms
- Property terms
- Action terms

Prepositions and conjunctions will also be available, but are a less integral part of the template and will be discussed in the usage of this method in Section 4.5. Adjectives may be entered as well when an entity is recorded. This feature will be explained in Section 4.3.1. Adverb, however, are currently not used in the Functional Description Template. This omission is due to the fact that such terms were found to be non-essential to describing a function and merely offer additional information. However, the addition of adverbs to the template could be completed at a later time.

The three primary elements (entities, properties, and actions) will be used to fill in the elements of the templates that are provided and are entered by the user through a combination of freeform text entry and menu selection. However, the user is required to identify all of the entities and properties before proceeding to record the functional statements in the provided templates. By doing so, the user is able to completely define

the use environment of the product before describing its functionality. This concept of the use environment is described in the next section.

4.2 Use Environment

The functional statements that describe the functionality of a product are describing the interaction of the product with its use environment. In the examples from the previous section, functional statements were shown to contain action terms, entity terms, and property terms. In a functional statement, the action term is describing the interaction between the product and an entity or property, where this entity or property is part of the use environment.

The use environment is defined as the set of entities and their properties with which the product interacts in its lifetime to carry out its intended functions. These entities are objects, whether they are physical or non-physical, on which the functions of the product will be acting. The use environment consists of two types of entities. The first type of entity is referred to here as an external entity and is what the use environment is most commonly said to contain. External entities are external to the product and are present regardless of its design. Such entities are commonly inputs or outputs of the system. The relevant properties of these entities are also identified as part of the use environment. A property is defined as any relevant quantity or attribute of an entity that may be used in describing the functions of the product.

Consider the VCUUV, the bio-inspired underwater vehicle used to detect underwater mines. The external entities for this vehicle and their properties could include the following:

- Operator
- Water
    - Depth
    - Velocity
- Mines
    - Location
    - Volume
- Electrical energy

These external entities interact with the vehicle regardless of its design and must be identified because a functional description of the product will describe their interaction with the vehicle. Clearly, many properties of external entities may be identified. In the example above, only a few properties were listed. These are the properties that are relevant in the functional description of the vehicle.

When describing the functions of a product it is often necessary to refer to the product itself or a component of the product. For this reason, a second type of entity can be identified in the use environment. This type of entity is referred to here as an internal entity and is allowed to be part of the use environment as a matter of convenience. An internal entity is defined as an entity that describes the product itself or components of

the product. For the example of the VCUUV, the internal entities and their properties could include the following:

- Vehicle
    - Length
    - Velocity
    - Location
- Power source
    - Lifetime
- Steering mechanism

These entities and properties are part of the product, but are identified as part of the use environment because they are used to specify the functions of the product.

The use environment of a product is an established concept; however, it is often only used implicitly when describing the functions of a product. In many other methods, when the user is recording a functional statement and uses nouns, these terms are likely referring to entities and properties in the use environment. In the Functional Description Template, the user is first asked to explicitly identify all entities and properties in the use environment. The user identifies the entities and properties in their own words and then maps their terms to those in a provided list. Mapping the user's terms to those in a basis will facilitate the retrieval of the product functions in a future search. When archiving the functions, the entities and properties that are identified by the user are used in conjunction with action terms to form functional statements in the provided templates.

An overview of this process for using the Functional Description Template is shown in Figure 18. This figure illustrates the archival of the function “regulate velocity of vehicle” for the bio-inspired VCUUV.

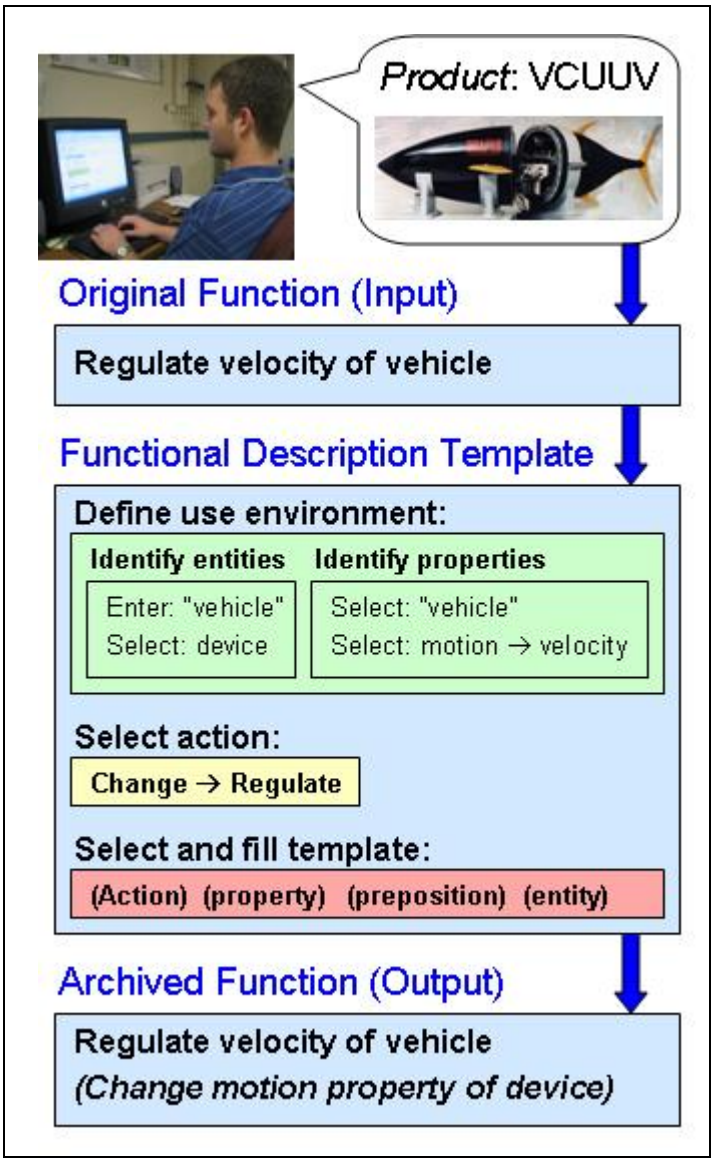


Figure 18: Overview of the Functional Description Template

In order to archive the function “regulate velocity of vehicle”, the user first defines the use environment of the product, which includes identifying “vehicle” as an entity and

“velocity” as a property of that entity. Both the entity and property are mapped to terms from a basis. Then, by selecting an action term and filling in the selected template, the function can be recorded as “regulate velocity of vehicle”. This function is also recorded using the terms from the basis that were selected, which results in the more general function “change motion property of device”. This representation is used to facilitate future searches based upon function. This entire process of recording a functional statement will be explained in greater detail in Section 4.5.

4.3 Terminology

In the following sections, the details of the three types of primary terms (entities, properties, and actions), with respect to their use in the Functional Description Template, will be described. Following this description, the details of the templates will be explained.

4.3.1 Entity Terms

Entity terms are nouns that are being acted upon by the action term in a functional statement. Allowing freeform text entry causes great difficulty in archiving and retrieving functional descriptions. Therefore, menu selection appears to be the best method for recording entity terms. However, the specificity of the entity being acted upon greatly defines the product being described and therefore provides useful information. As a result, the approach to recording entity terms is to allow for freeform text entry to capture the exact entity being acted on, but require that the entity be mapped or classified through

menu selection to facilitate archiving and retrieving the functional description. For this classification, a two-level hierarchy of entity types was created.

The high-level entity type, which is chosen by menu selection, is divided into 7 types of entities. These entities, along with their definitions, are as follows:

- **Living entity**: An individual form of life (organism) or a biological component (organs, organelles, etc.) that works together to carry on the various processes of life.

- **Artifact**: A structure not normally present, but produced by an external agent or action. An object produced or shaped by human craft, as distinguished from natural objects.

- **Material**: A tangible substance that goes into the makeup of a physical artifact.

- **Particle**: One of the minute subdivisions of matter. A body having finite mass and internal structure, but negligible dimensions.

- **Wave**: A disturbance traveling through a medium which transfers energy from one particle of the medium to another without causing any permanent displacement of the medium itself.

- **Energy**: The capacity of a physical system to do work.

- **Space**: An extent or expanse of a surface or volume; a blank or empty area.

- **Data**: Numbers, characters, images, or other method of recording, in a form that can be assessed by a human or (especially) input into a computer, stored and processed there, or transmitted on some digital channel.

For each of these entity types, a second menu of entity types is provided to allow for further specification. For example, shown below are the terms and definitions in the secondary menu for the entity type “Material”.

- **Solid**: A substance that does not flow perceptibly under moderate stress, has a definite capacity for resisting forces (as compression or tension) that tend to deform it, and under ordinary conditions retains a definite size and shape. May include composite materials and particulates.

- **Liquid**: A substance that has no fixed shape but a fixed volume and exhibits a characteristic readiness to flow, little or no tendency to disperse, and relatively high incompressibility.

- **Gas**: A substance that has neither independent shape nor volume and is characterized by relatively low density and viscosity, relatively great expansion and contraction with changes in pressure and temperature, the ability to diffuse readily, and the spontaneous tendency to become distributed uniformly throughout any container.

- **Plasma**: An electrically neutral, highly ionized gas composed of ions, electrons, and neutral particles. A phase of matter distinct from solids, liquids, and normal gases that is often found in stars and fusion reactors.

- **Mixture**: A composition of two or more material substances, in varying proportions, that are not chemically combined with each other and are capable of being separated.

Similar lists exist for each of the primary entity types, with the exception of “Space”, which requires no secondary list. For all terms available in both lists of entity types, definitions of the term are listed to aid the user. A complete list of entity terms and definitions is provided in Appendix B1.

This method of recording the entity terms offers the advantages of both freeform text entry and menu selection. The user is able to type in the entity in their own words, preserving information about the entities that interact with the product. Such information may include adjectives which describe the entities. When recording the entity, the user is able to type in any additional terms that may provide useful information. Then by mapping the entity term to a standardized entity type, future searches will be able to quickly retrieve products that operate on various entities that are of the same classification. The details of this search method will be explained in Section 6.3.

4.3.2 Property Terms

The second type of term that can be recorded in a functional statement is a property term. These terms are nouns that describe some aspect of an entity. As with recording entities, properties are recorded using a combination of freeform text entry and menu selection. The freeform text entry allows for the user's own language to be retained, while the association with a menu selection facilitates a later search for the information. However, unlike entering entities, the text entry is optional for recording properties. Property terms are provided in a two-level hierarchy and are chosen through menu selection. If the user selects "*Other", they will be able to type in any property.

In the two-level hierarchy of properties, the first level is a classification of properties into nine categories. These categories, along with their definitions, are shown below.

- **Chemical**: Any property that describes a chemical or the action of a chemical.
- **Electromagnetic**: Any property related to the behavior of electric or magnetic fields.
- **Failure**: Any property describing the mechanical failure of a material.
- **Geometric**: Any property that describes a spatial relationship.
- **Material**: Any property that describes some aspect or behavior of a material.
- **Mechanics**: Any property related to energy and forces and their effects.
- **Motion**: Any property related to the manner in which a body changes position with respect to time.
- **Thermo-physical**: Any property that describes the behavior of heat or its interaction with other bodies.

- **Waves**: Any property that describes an aspect of a wave, such as a sound wave or electromagnetic wave.

The user must first make a selection from this list of categories. Upon making a selection, the second level of the hierarchy is provided which contains an extensive list of properties for the selected category. An example of properties that are provided in the second-level menu is shown below for the category of thermo-physical properties.

- Boiling point
- Enthalpy
- Entropy
- Freezing point
- Melting point
- Specific heat
- Temperature
- Thermal conductivity
- Thermal energy
- Thermal expansion coefficient
- *Other

The user may choose to select a property from this list or select "*Other" and enter a property through freeform text entry. Regardless of whether a property is selected from those provided or typed in by the user, both the property and its classification in the first level will be recorded.

For every property that is available, a definition and the units of measure, if it is a quantifiable property, are provided. A complete list of the property types and provided properties, along with definitions, is provided in Appendix B2. An example of the information provided for a property is shown below for the property “temperature”.

- Property term: Temperature
- Property type: Thermo-physical
- Definition:
  - The degree of hotness or coldness of a body or an environment as indicated on or referred to a standard scale.
- Units:
  - Fahrenheit (°F)
  - Celsius (°C)
  - Kelvin (K)

4.3.3 Action Terms

Every functional description begins with an action term to indicate what action is required for that function. This action term, if left to the user, could be any of several thousand possible verbs. This variety in language makes retrieving functional descriptions more difficult. To remedy this problem, a fixed set of action terms is provided to the user for menu selection. The possibility of allowing a freeform text entry that is mapped to a selected action term was considered. However, the variety and complexity of verbs forced this option to be discarded. An example of this problem is seen in noun-specific verbs. Some verbs imply a noun that is being acted upon. For example, the verb “to drink” implies that a liquid is being taken in. To preserve all possible information it is necessary to decouple the entity and action terms. Other difficulties exist as well if the user were allowed to enter any verb. Therefore, action

terms are selected from a fixed set. However, this list of action terms differs from a functional basis and, therefore, is not subject to many of the limitations of that method.

A functional basis provides terms that are arranged in a hierarchy and that are often not common words. In the Functional Description Template, a single list of 30 basic action terms is provided. This list of terms was collected by using an existing functional basis as a starting point, the functional basis developed by Hirtz and Stone [Hirt02]. First, a complete list of terms was compiled from all levels in the hierarchy of terms. Additionally, the correspondent terms from the published basis, words that may be represented by the functional basis terms, were also considered. Many of the terms that appeared in this compiled list appear as one of the final 30 action terms. In order to simplify the list of terms, any term that was determined to have the same basic meaning as another term was removed from the list. By removing some of the synonymous low-level terms and general high-level terms from the functional basis, a shortened list of action terms was established with no hierarchical structure. From the remaining list of action terms, some terms were then changed to a more familiar word from everyday speech. Words were chosen that were not specific to either engineering terminology or biological terminology. These 30 actions, along with a brief definition from The American Heritage Dictionary of the English Language [Pick00], are shown below and can also be found in Appendix B3. The action terms are listed in an order that groups together similar terms, as well as antonyms.

1. **Create**: To cause to exist
2. **Copy:** To make a reproduction

3. **Destroy:** To ruin completely
4. **Provide:** To make available
5. **Acquire:** To gain possession of
6. **Remove:** To take away
7. **Inject**: To force or drive into
8. **Eject**: To throw out forcefully
9. **Move**: To change the place or position of
10. **Rotate:** To turn around on an axis or center
11. **Position:** To put in place or position
12. **Guide**: To direct the course of
13. **Collect**: To bring together in a group
14. **Disperse:** To drive off or scatter in different directions
15. **Connect:** To join or fasten together
16. **Mix**: To combine or blend into one
17. **Separate**: To set or keep apart
18. **Contain**: To hold or keep within limits
19. **Secure**: To make firm or tight
20. **Change**: To cause to be different
21. **Maintain**: To keep in an existing state
22. **Start**: To set into motion, operation, or activity
23. **Stop**: To halt the motion or progress of
24. **Increase**: To make greater or larger
25. **Decrease**: To grow or cause to grow gradually less or smaller

26. **Detect**: To discover or ascertain the existence, presence, or fact of
27. **Measure**: To ascertain the dimensions, quantity, or capacity of
28. **Communicate**: To convey information about
29. **Record**: To set down for preservation in writing or other permanent form
30. **Specify**: To state explicitly or in detail

In addition to a brief definition, each action term also has a long list of synonyms associated with it. Although the list of 30 action terms represents most basic actions, the user may have a different term in mind. For this reason, a large list of synonyms was created for each of the action terms. In order to create a thorough list, many troponyms were identified using WordNet [Mill03] and were also included in the list of synonyms. Troponyms are verbs that express a more specific action of another verb. For example, “march” is a troponym of “walk” because it is one specific way of walking. By including several possible synonyms and troponyms for the 30 action terms, a user has the ability to select from over 800 action terms. A complete list of the available synonyms for each action term is provided in Appendix B4.

Another important attribute of the action terms is their usage. Action terms may be used in a variety of sentence structures to convey different information. It is for this reason that more than one template will be available to form functional statements. The templates that are available and their correct use are described in Section 4.4. Shown below is an example of a primary action term and its corresponding attributes.

- Action term: Detect
- Definition: To discover or ascertain the existence, presence, or fact of
- Synonyms: Ascertain, Discover, Distinguish, Expose, Feel, Find, Hear, Identify, Listen to, Locate, Notice, Observe, Perceive, Read, Receive, Recognize, See, Sense, Sight, Smell, Spot, Taste, Trace, Uncover
- Usage:
    - Detect (entity)
        - Ex: See light
    - Detect (property) of (entity)
        - Ex: Sense motion of vehicle
    - Detect (entity) (preposition/conjunction) (entity)
        - Ex: Detect salt in water

The organization of action terms as described above offers many benefits to the user. First, despite the large number of total action terms, the menu selection remains simple by requiring a choice from a single list of 30 action terms rather than requiring multiple selections from a hierarchy of terms. The selection of a synonym is optional and only serves to aid the user in matching a primary action term to the function being expressed. Secondly, the list of synonyms is extensible and in the future could allow for users to add terms to the list. Another advantage is found in the archival and retrieval of the functional descriptions. While many possible action terms are available, they remain associated to one of the 30 primary action terms. Therefore, when searching for products by function, all synonyms of the desired action term are searched. This feature will be discussed in detail in Section 6.3.

4.4 Templates

Using the terms that were described in the previous sections, one can record functional statements using the Functional Description Template as implemented in the data entry

form. This process is completed by selecting a standardized template and filling in the desired terms. While many templates could be created, three templates were determined to be the most commonly used in describing the function of a product or concept. These three templates take the following forms:

1. (Action) (entity)
2. (Action) (property) of (entity)
3. (Action) (entity) (preposition/conjunction) (entity)

The first template is used to form the most basic functional statements and results in a simple verb-noun sentence. Functions that may be created using this template include “contain water” and “detect mines”. The second template is used to record a function that performs an action on a property of an entity. For example, this template may be used to record the function “increase velocity of water” or “detect position of mines”. The final template is used to record functions that include a prepositional phrase or describe the actions on two entities. Such functions may include “propel vehicle through water”, “remove battery from robot”, or “eject pilot and seat”. The steps necessary to record such functions are described in the next section.

4.5 Functional Description Template Usage

The data entry form, which implements the Functional Description Template, breaks up the process of recording functions into a number of steps to facilitate the process for the user. In order to record the functions of the product into the repository, the following steps must be taken:

1. Define use environment
    a) Identify entities
    b) Identify properties
2. Record functions

A screenshot of the section of the data entry form using the Functional Description Template is shown in Figure 19.

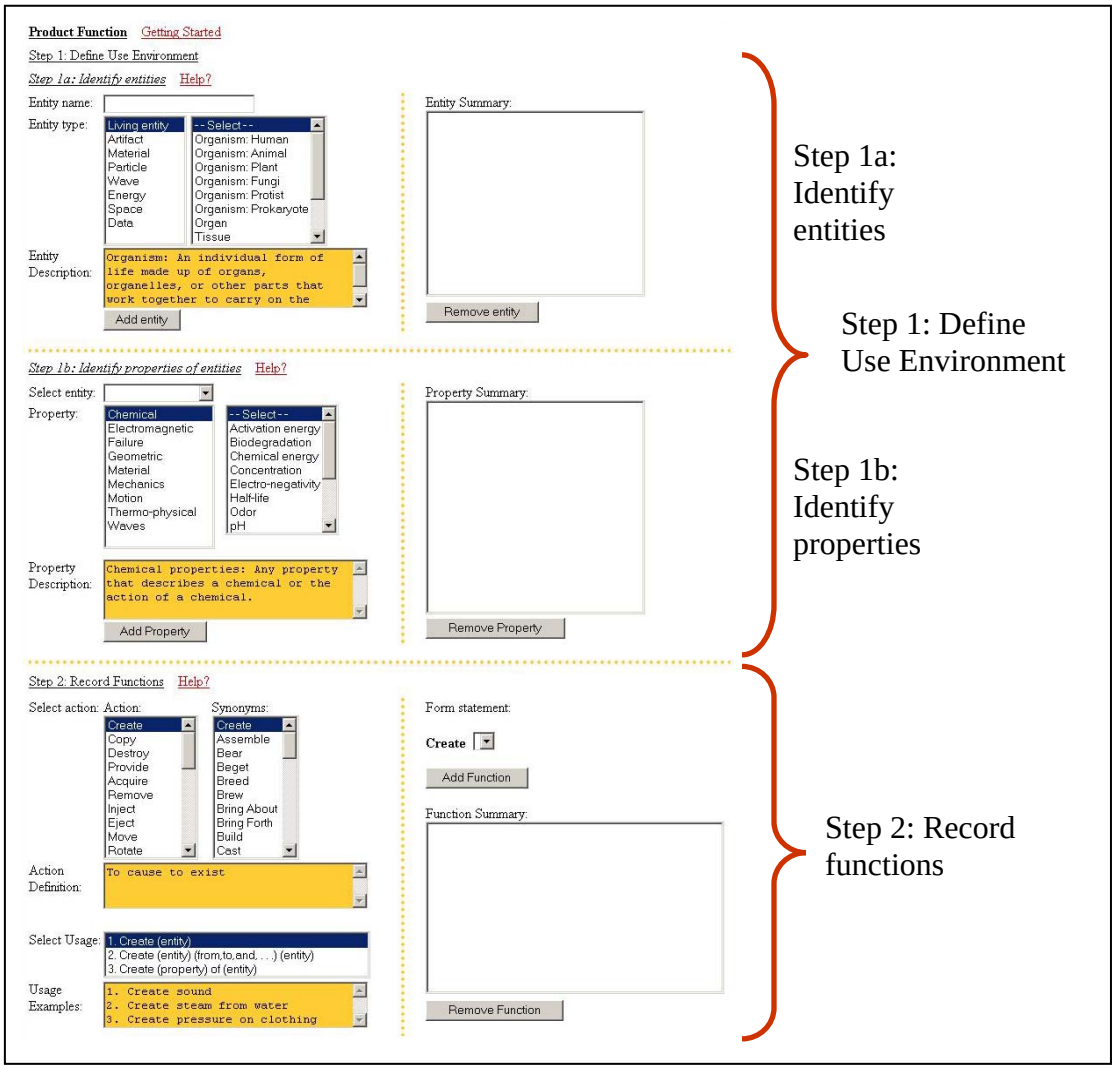


Figure 19: Functional Description Template

To help illustrate the use of the Functional Description Template, these steps will be explained in the following subsections while being implemented for the archival of a bio-inspired mobile robot. Consider the following scenario. A research group has developed an unmanned underwater vehicle that is inspired by the morphology and kinematics of the yellow-fin tuna to be used for underwater mine reconnaissance [Ande99]. In an effort to inspire future work, the engineers decide to archive this new product into the repository of bio-inspired products. The engineers use the data entry form to record all of the required information. In order to record the functions of this device, the engineers must then use the Functional Description Template. In some cases, the users may already have developed a functional description of the product and can use those statements as a starting point. In this case, we will assume that no functional descriptions have yet been developed.

4.5.1 Step 1: Define use environment

As explained earlier, the Functional Description Template requires the user to first explicitly define the use-environment of a product, where the use environment is defined as the set of entities and their properties with which the product interacts in its lifetime to carry out its intended functions. This procedure is carried out first because the entities and properties of the use environment are referred to in the functional statements of the product that will be recorded.

For the above example of the tuna-inspired robot, the following entities and properties are identified:

- Operator
- Water
    - Depth
    - Velocity
- Mines
    - Location
    - Volume
- Electrical energy
- Vehicle
    - Length
    - Velocity
    - Location
- Power source
    - Lifetime
- Steering mechanism

In the next two steps, these entities and properties are recorded and mapped to the necessary terms.

4.5.2 Step 1a: Identify entities

In this step, the user identifies all the entities in the use-environment and records them one at a time. Referring to Figure 20, to add an entity, the following steps are employed:

1. In the box next to "Entity name", the user types in the name of the entity to be added.

2. Using the lists in the two columns next to "Entity type", the user specifies the type of entity that is being added. This information will be archived for future searches. In the first column, the user selects the category that best describes the entity. Then, in the second column, the user selects a more specific entity type from the chosen category. Definitions of the selected term are provided in the yellow box below the list labeled "Entity Description."

3. The user adds the entity by clicking the "Add entity" button. Once added, the entity name and type will appear in the "Entity Summary" list on the right side of the screen. To remove an entity from the list, the user selects the added entity and then clicks the "Remove entity" button.

In the case of the tuna-inspired robot, to enter the entity “vehicle”, the user first types in “vehicle”. Next, the user selects the category “Artifact”, which describes a man-made object, and then selects “Device” which describes a mechanism that uses several components to function (the vehicle). This entity can then be added by clicking the “Add entity” button. These steps are then repeated for the remaining entities. In Figure 20, a screenshot shows these steps being followed for the entry of the tuna-inspired vehicle. In this figure, three entities have been previously added and the entry of the entity “vehicle” is shown.

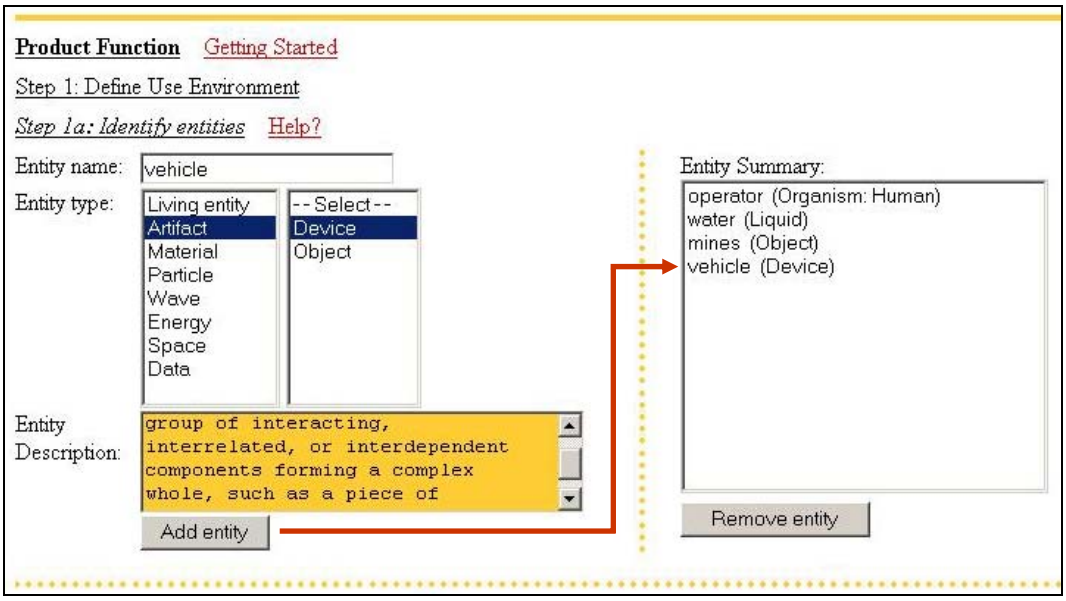


Figure 20: Functional Description Template – Step 1a

4.5.3 Step 1b: Identify properties

In this step, the user identifies any properties of the entities that were added in the previous step that are of importance in the use of the product. Properties are entered one at a time and associated with the entity of which they are a property. Referring to Figure 21, to add a property, the following steps are employed:

1. In the menu next to "Select entity", the user selects the entity to which a property will be added. All of the previously identified entities will appear in this menu.

2. Using the lists in the two columns next to "Property", the user selects the property to add. In the first list, the user selects the type of property to be added. Then, in the second list, the user selects a property. If "*Other" is chosen from the end of the list, the user types in the property in the text box that appears below the list. Definitions of the selected term are provided in the yellow box below the list labeled "Property Description".

3. The user adds the property by clicking the "Add property" button. Once added, the property and the entity to which it belongs will appear in the "Property Summary" list on the right side of the screen. To remove a property from the list, the user selects the added property and then clicks the "Remove property" button.

In the case of the tuna inspired robot, to enter the property “velocity of vehicle” for example, the user would select “vehicle” from the menu of added entities. Next, “Motion” would be selected as the type of property, and then “velocity” would be selected as the property. If this term were not available, the user would select “*Other” and then proceed to type in “velocity”. Once the property is selected or typed in, it can be added by clicking the "Add property" button. These steps are then repeated for the remaining properties. These steps are shown in Figure 21 for the example of the tuna-inspired vehicle. In this figure, five properties have been previously added and the entry of the property “velocity” for the entity “vehicle” is shown.

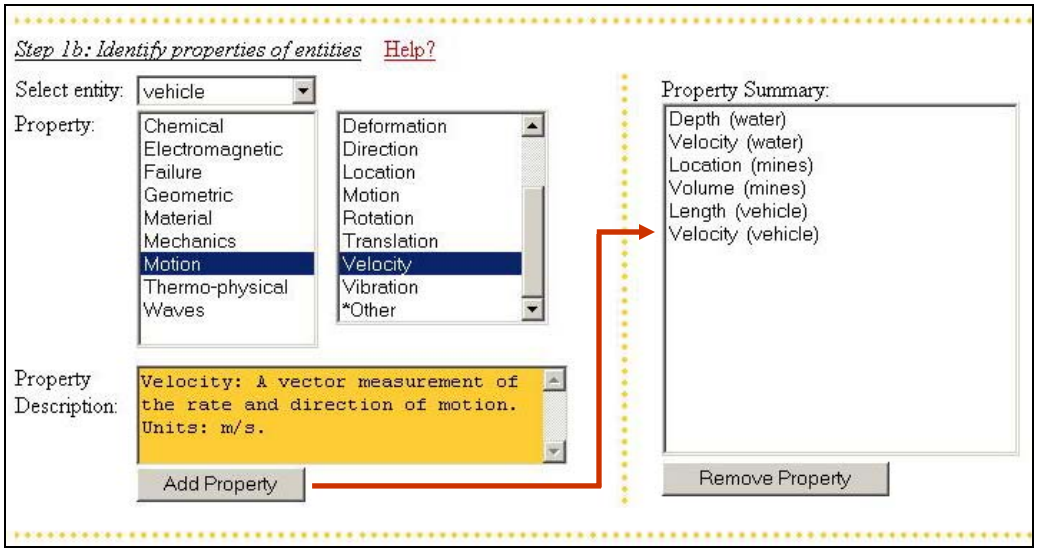


Figure 21: Functional Description Template – Step 1b

4.5.4 Step 2: Record functions

In this step, the user forms the functional statements using the entities and properties that were previously identified and then records them one at a time. Referring to Figure 22, to record each functional statement, the following steps are employed:

1. Using the menus in the two columns next to "Select action", the user selects the action term that most accurately represents the functional statement. The first menu provides 30 action terms from which to choose, and the second menu provides a list of synonyms for each these terms. Definitions of the 30 action terms are provided in the yellow box below the menus labeled "Action Definition".

2. Using the menu next to "Select Usage", the user selects the sentence structure of the functional statement that will subsequently be recorded. The first option is for simple verb-noun functions, such as “store water”. The second option is for functions that use more than one entity, such as “allow water into iron”. The last option is for functions that use a property, such as “adjust base temperature”.

3. On the right side of the screen, the functional statement is now formed. The selected action term will already be present and drop-down menus are used to select the desired entities or properties. If required, a text box will be provided to enter prepositions. If the desired entity or property does not appear in the menus, the user may return to Step 1 to add it.

4. The user adds the functional statement to the “Function Summary” by clicking the "Add Function" button. To remove a functional statement from the list, the user selects the function and then clicks the "Remove function" button.

In the case of the tuna-inspired robot, to enter the functional statement “regulate velocity of vehicle”, first the action term “change” is selected since it has the closest in meaning to the term “regulate”. The synonym “regulate” is then selected from the second menu. Next, the third usage is selected to record a functional statement that describes a property. The correct template will now appear on the right side of the screen with the action term “regulate” already present. The property “velocity” is selected from the first menu, causing the associated entity “vehicle” to appear in the functional statement. Then, the preposition “of” is typed into the provided text box. The functional statement “regulate velocity of vehicle” can now be added by clicking the "Add Function" button and these steps can then be repeated to record the remaining functional statements for the product. These steps are shown in Figure 22 for the example of the tuna-inspired vehicle. In this

figure, two functional statements have been previously added and the entry of the functional statement “regulate velocity of vehicle” is shown.

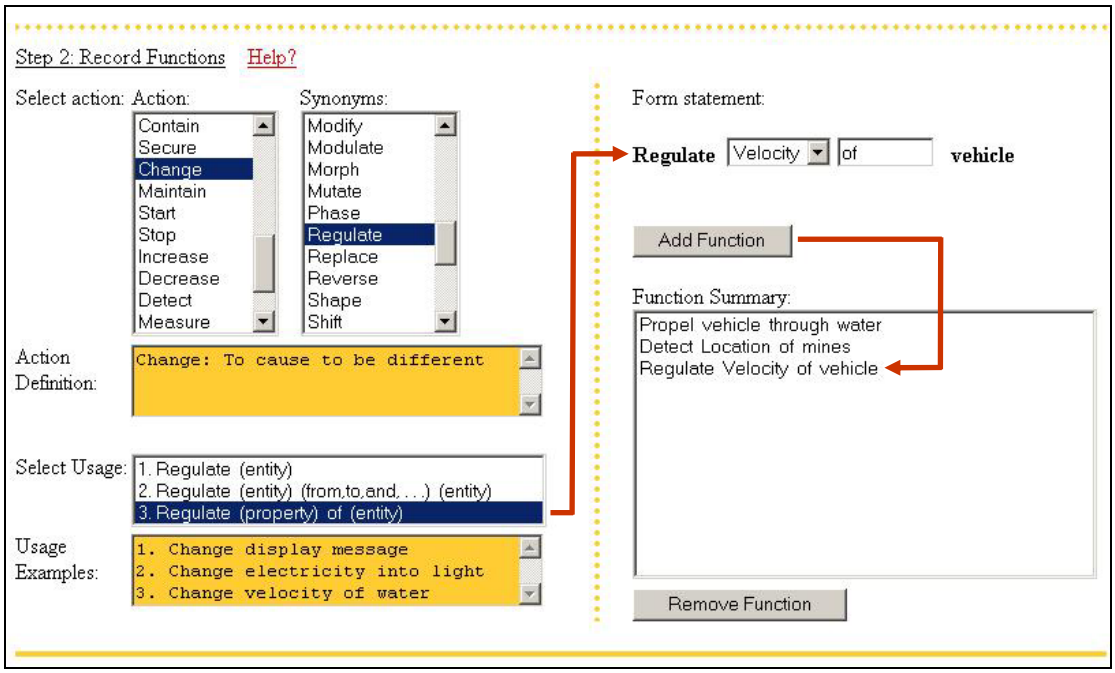


Figure 22: Functional Description Template – Step 2

Once a functional statement is submitted to the repository using the Functional Description Template, several fields are recorded for that function. In addition to the entire functional statement being recorded, each action, entity, and property term is stored separately along with their classifications. For example, for the recorded function “regulate velocity of vehicle”, the archived terms include the action term “change”, the property type “motion”, the entity type “device”, and the high-level entity type “artifact”. This information is not shown to the user, but is needed for function searches to yield the best results. Details of this search method are explained in Section 6.3.

Using the Functional Description Template as described in the above example, the high-level functions were recorded for the 89 bio-inspired products that were archived into the repository. These recorded functions, using the user's terminology, are provided in Appendix A2. The additional fields that are recorded to store the classifications of all the terms are provided in Appendix A3.

Chapter 5: Evaluation of the Functional Description Template

The Functional Description Template offers several advantages over existing methods for recording the functional information of products. However, in order to confirm these advantages and measure the degree of improvement over an existing alternative, an evaluation of the Functional Description Template method was conducted. This study provided a direct comparison between the Functional Description Template (FDT) method and the Functional Basis (FB) method. Two web-based applications were developed that implemented each of these methods for the recording of functional statements. For the form that implemented the Functional Basis method, the basis that was discussed previously in Chapter 2 was used [Hirt02]. Both applications provided the user with definitions for all of the terms that were available, as well as help files that contained instructions and an example. A complete list of the function terms and flow terms used in the Functional Basis method, along with definitions and examples, are provided in Appendix C1 and Appendix C2, respectively. Additionally, the help files for the Functional Description Template method and the Functional Basis method are found in Appendix B5 and Appendix C3, respectively.

5.1 Approach

The study was conducted with 12 students who remained anonymous when submitting their work. In order to obtain this sample, students were asked to volunteer for the study and told that they would be comparing two methods for recording functional statements. The students who were asked to participate were mechanical engineering students that were undergraduate seniors or graduate students. This limitation was imposed to ensure

that the participants had a good understanding of the functional description of mechanical devices.

The study asked the participants to identify the functions of a common product and then record those functions using two different web-based applications, one that employed the Functional Basis method and one that employed the Functional Description Template method. Both of these steps, identifying the functions and then recording them, were performed by the participants without any time limitations. The product that was assigned for this study was a “portable music CD player”. Before the participants began, a brief tutorial was given to provide them with the necessary background information to complete the study. The study was designed to compare the two methods being employed, not the participants’ prior knowledge. Therefore, the tutorial explained the concepts of the use environment and functional decompositions as they are used to describe a product. Several examples were also provided. This tutorial helped to ensure that the participants were equally capable of completing the study. The slides that were presented in the tutorial are given in Appendix D1.

After the tutorial, the participants were given instructions for Part I of the study, which required them to identify the use environment and functions for a portable music CD player. The participants typed up the use environment for the product, including the relevant entities and properties, and then performed a functional decomposition for 3 levels of decomposition as explained in the instructions, which are provided in Appendix D2. Each functional statement in the decomposition was also assigned a unique number

that would be recorded in both applications to allow for comparison. An example of a functional decomposition for the CD player, as performed by the participant identified as User 102, is shown below.

- FR0: Play CDs using own power source.
    - FR1: Spin CD
        - FR11: Facilitate installation of CD
        - FR12: Secure CD
        - FR13: Rotate CD at optimal RPM
    - FR2: Provide anti-skip protection
        - FR21: Store data
        - FR22: Sense a skip in the CD
        - FR23: Replace missing data
    - FR3: Convert to sound
        - FR31: Receive data from CD
        - FR32: Convert to sound
    - FR4: Broadcast sound
        - FR41: Amplify sound
        - FR42: Transfer sound to speakers
        - FR43: Focus sound to user
    - FR5: Use portable power source
        - FR51: Generate DC electrical energy
        - FR52: Facilitate replacement of power source
    - FR6: Read data from CD

- FR61: Focus laser
- FR62: Transmit data

Once Part I was completed, the documents were anonymously uploaded to a server so that changes could not be made to the initial work. Once all documents were received, instructions for Part II of the study were distributed.

This second set of instructions, given in Appendix D3, informed the participants of the two websites where the two different applications were located. The participants were instructed to use each application to record each of the functional statements from their decompositions in order, and the identification numbers that the functions were assigned. The participants were also instructed that their objective was to enter or select the terms that most accurately represented the function that they originally typed, even if changes had to be made to their terminology. Also, they were instructed that, despite the changes, if they felt that they were unable to record a functional statement in a way that retained its basic meaning then they were to skip that function. Lastly, the participants were instructed to consult the help files, which were accessible through "Help?" links that appeared throughout the applications, for instructions and examples. Once the participants completed each application, they clicked a submit button that sent their recorded functions via an anonymous email.

A screenshot of the application employing the Functional Basis method is shown in Figure 23.

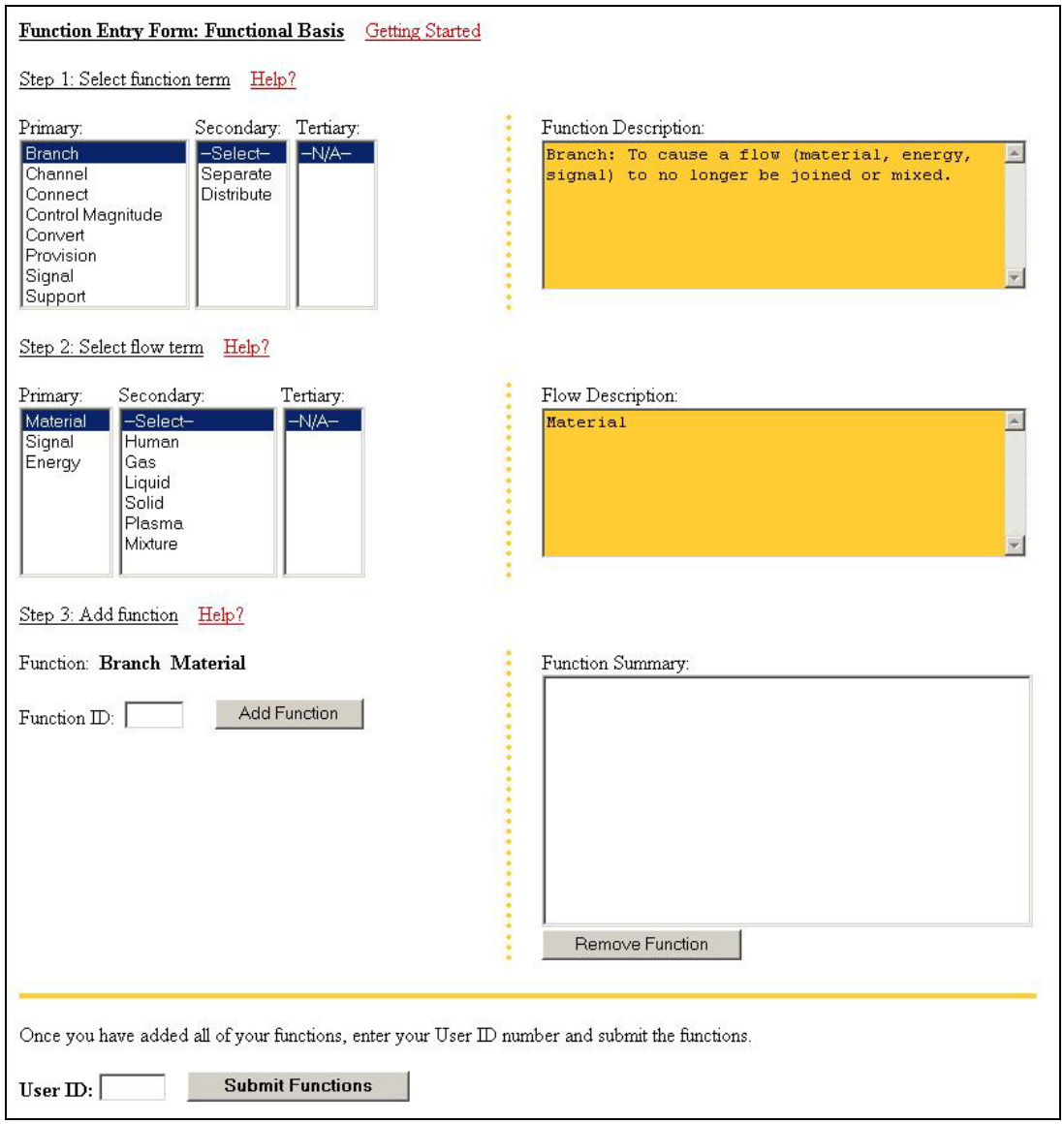


Figure 23: Functional Basis Form used in the study

To demonstrate the results of using this application, the functions that were recorded by User 102 from their functional decomposition are shown below.

- FR0: Convert Auditory Signal
    - FR1: Rotate Object Material
        - FR11: Join Object Material
        - FR12: Secure Object Material

        - FR13: Regulate Object Material
    - FR2: Stabilize Signal
        - FR21: Collect Signal
        - FR22: Detect Signal
        - FR23: Process Signal
    - FR3: Convert Signal
        - FR31: Collect Analog Signal
        - FR32: Convert Signal
    - FR4: Distribute Signal
        - FR41: Process Signal
        - FR42: Transmit Auditory Signal
        - FR43: Channel Auditory Signal
    - FR5: Convert Electrical Energy
        - FR51: Supply Electrical Energy
        - FR52: Supply Electrical Energy
    - FR6: Detect Analog Signal
        - FR61: Channel Electrical Energy
        - FR62: Transmit Signal

To illustrate the changes that are made to the user's functions by using this method, consider the original function FR43 - Focus sound to user. This function has been recorded as "Channel auditory signal", which changes the user's original terminology.

A screenshot of the other application, which employs the Functional Description Template method, is shown in Figure 24. This application is part of the complete data entry form that was shown in Section 4.5.4. In this version, only the section for recording functions is presented and two fields have been added to record the user's identification number and the function identification number for each function. This additional information was necessary for the evaluation of the two methods.

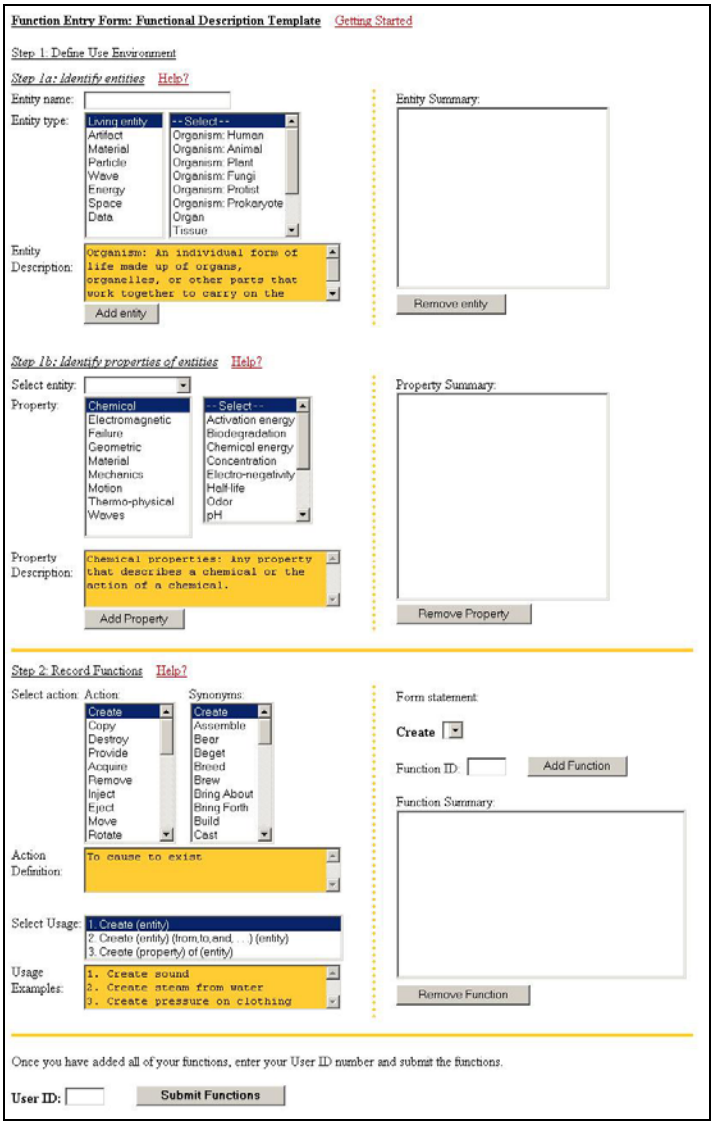


Figure 24: Functional Description Template Form used in the study

The functions that were recorded by User 102 using this application are shown below.

- FR0: Play CDs using Power Source
    - FR1: Spin CDs
        - FR11: Insert CDs
        - FR12: Secure CDs
        - FR13: Spin CDs
    - FR2: Provide Memory
        - FR21: Store Memory
        - FR22: Sense Memory
        - FR23: Insert Memory
    - FR3: Convert Sound
        - FR31: Receive CDs
        - FR32: Convert Sound
    - FR4: Play Sound
        - FR41: Amplify Sound
        - FR42: Transfer Sound to Speakers
        - FR43: Focus Sound to User
    - FR5: Use Power Source
        - FR51: (Not recorded)
        - FR52: Remove Power Source
    - FR6: Collect Sound from CDs
        - FR61: Focus Laser

        - FR62: Communicate Sound

Notice that this method allowed the user to record the original function, FR43: Focus sound to user, exactly as it was originally stated.

The recorded functions shown above include the terms that the user entered into the Functional Description Template. However, this method also archives the classification of these terms to facilitate a later search of this information. The classifications of the above functions that were recorded by User 102 are shown below.

- FR0: Start object using electrical energy
    - FR1: Rotate object
        - FR11: Inject object
        - FR12: Secure object
        - FR13: Rotate object
    - FR2: Provide device
        - FR21: Contain device
        - FR22: Detect device
        - FR23: Inject device
    - FR3: Change sound wave
        - FR31: Detect object
        - FR32: Change sound wave
    - FR4: Start sound wave
        - FR41: Increase sound wave

        - FR42: Move sound wave to device
        - FR43: Guide sound wave to human
    - FR5: Start electrical energy
        - FR51: (Not recorded)
        - FR52: Remove electrical energy
    - FR6: Collect sound wave from object
        - FR61: Guide device
        - FR62: Communicate sound wave

Notice that the function “FR43: Focus Sound to User” is classified by the system as “FR43: Guide sound wave to human”. This classification allows other functions with similar classifications to be retrieved in a search. This feature will be described in Section 6.3.

Once the participants recorded all of their functions using both applications, as shown for User 102, they completed a brief evaluation sheet and anonymously uploaded the results to the server. All of the participants’ documents (initial functional decomposition, both sets of electronically submitted functions, and the evaluations) contained a user identification number so that they could be matched. Also, the author performed the same steps as the participants prior to the study to test both methods’ ability to record the functions for the CD player. These results, available in Appendix D4, illustrate what information expected from the participants.

5.2 Measures

This evaluation compared the Functional Description Template to a Functional Basis based upon the following five distinct measures.

- Expressiveness
- Correctness
- Information loss
- Categorization
- Ease of use

Expressiveness refers to the ability of the method to record a functional statement as it was initially expressed by the user. For this measure, each functional statement that was recorded by each method was compared to the original function from the user's functional decomposition. The terms that appeared in both the original function and the recorded function were then counted. A term was identified to be a match if it was either identical or a related form of the same word. For example, if one function contained the word "electricity" and the recorded function used the term "electrical", then that term was counted as a match. Also, inconsequential terms such as prepositions, conjunctions, or articles (e.g. the, and, from, etc.) were not counted. For example, function FR43 recorded by User 102 was "Focus sound to user". Using the Functional Basis method, this function was recorded as "Channel Auditory Signal". The terms "focus", "sound", and "user" do not appear in this representation and therefore no matched terms were counted. The same function was recorded using the Functional Description Template method as "Focus Sound to User", resulting in all three terms being matched. Performing this analysis for

all functions, it was assumed that the best method was the one that allowed the user to record functions that contained a greater number of matched terms.

Correctness is a measure of the user's ability to use the method successfully to record the functional statement. The correctness of a recorded function was determined by judging whether the recorded terms portrayed the same meaning as those being represented from the original function. This judgment was made by the author based upon the definitions of the recorded terms from either method. All recorded functional statements were marked as being correct, partially correct, or incorrect. Correct functions were those in which all recorded terms accurately represented the meaning of a term from the original function. Partially correct functions were those in which at least one, but not all, of the recorded terms were correct. Incorrect functions were those in which no recorded terms accurately represented the meaning of the original terms, or no terms were recorded at all. For example, the function "Focus sound to user" recorded by User 102, was recorded in the Functional Basis method as "Channel Auditory Signal". This function was marked as being correct because the term "channel" accurately represents the term "focus" and the term "auditory signal" accurately represents the term "sound". In evaluating the correctness of the functions, the terminology and any lost information is not considered. Using this approach, it was assumed that the best method was the one that allowed the user to record more correct functions and was therefore more successful at recording the intended meaning of the user's original functional statements.

Information loss is a measure of each method's ability to retain the information expressed by the user. This differs from expressiveness in that the user's terminology is not being considered, only the quantity of information that is retained. An ideal method would have no information loss and retain all of the user's information. Determining the amount of information that is lost or retained is not as straightforward as counting matching terms. Any term or group of terms that describes an action or something being acted upon was deemed to be a piece of information. A group of terms could be considered a single piece of information if they described a single object. For example, the phrase "portable CD player" would be counted as one piece of information. Using this method, the pieces of information that appeared in the original function that were not recorded were counted. An example of information loss can be seen in the function "Focus sound to user", recorded by User 102. In the Functional Basis method, this function is recorded as "Channel Auditory Signal". The original terms "focus" and "sound" are represented by different words. However, the term "user" is not represented. There is no recorded information indicating where the auditory signal is being channeled. Therefore, for this function, one piece of information has been lost. This function in recorded in the Functional Description Template method as "Focus Sound to User" and therefore no information has been lost. This analysis allows for the comparison of each method's ability to record the complete functional information described by the user.

Categorization refers to the ability of each method to efficiently archive the user's functions by eliminating the large amount of variability in how a user records a function. The variability of a recorded function refers to the occurrence of multiple users recording

a function with the same meaning, but stated in a different way. For example, consider one function of a portable CD player – rotate the CD. Most of the participants in this study identified this function, but it was represented in several different ways. The variety in stating this function is shown in Table 1.

Table 1: Variability in user's original functions

User ID	Orginal Function
102	Spin CD
103	Spin the disc at a certain velocity
104	Spin the CD
201	Rotate Disc
202	Spin CD
205	Drive motor spins CD
302	Rotate CD
306	Spin CD at specific angular velocity
307	Spin CD

The ability to provide uniformity in the recorded functions was described earlier to be one of the benefits of the Functional Basis method, which accomplishes this by limiting the user to a basis of function and flow terms. The Functional Description Template allows the user to type in any terms, but also requires that these terms be mapped to a modified basis in order to offer the same benefit. In order to compare this feature of each method, the amount of reduction in the variability of the functional descriptions was analyzed. For each method, all of the recorded functions were counted, as well as the total number of unique functions. The number of unique functions does not count functions that have a literal representation identical to that of another function. The ratio of unique functions to the total recorded functions indicated how well the method reduced the variability in the users' functions. For both methods, the functions formed by terms from the lowest level of classification were used. An example of the reduction in

variability accomplished by each method is shown in Table 2 for the user's original functions from Table 1. Notice that the Functional Description Template method records the user's functions in their own terminology in addition to the classification.

Table 2: Categorization of recorded functions

User ID	FB	FDT	FDT Classification
102	Rotate Object Material	Spin CDs	Rotate Object
103	Rotate Solid-solid Material	Spin compact disk	Rotate Object
104	Rotate Object Material	Spin CD	Rotate Object
201	Rotate Object Material	Rotate disc	Rotate Object
202	Actuate Material	Spin CD	Rotate Object
205	Rotate Composite Material	Rotate CD using Drive motor	Rotate Solid using Device
302	Actuate Rotational Angular velocity	Rotate CD	Rotate Object
306	Control Magnitude Object Material	Spin CD	Rotate Object
307	Actuate Rotational Energy	Spin CD	Rotate Object

Ease of use was measured by having the participants complete a short evaluation form, which asked two questions and asked for comments, after using both methods to record their functions. The two questions helped to determine the user's preference regarding two specific attributes of the methods – the ability to locate the desired terms and the ability to record the intended function. After these two questions, the user was asked for any additional comments on the two methods. The contents of the evaluation form are shown below.

1. In both methods, you were required to select terms from provided lists. For all of your functional statements, in which of the two methods was it easier to locate the terms that you were seeking?

    a) Functional Description Template was much easier.
    b) Functional Description Template was a little bit easier.
    c) Both methods were about the same.
    d) Functional Basis was a little bit easier.
    e) Functional Basis was much easier.

2. In both methods, you were asked to record your functions as close as possible to how you originally typed them. For all of your functional statements, which method recorded functions that most accurately represented the functions you had originally typed?

    a) Functional Description Template was much more accurate.
    b) Functional Description Template was a little bit more accurate.
    c) Both methods were about the same.
    d) Functional Basis was a little bit more accurate.
    e) Functional Basis was much more accurate.

3. Please add any comments regarding the use of these two methods.

These five distinct measures provided a means to make a direct comparison between the Functional Description Template and a Functional Basis.

5.3 Results

Once the initial functional decompositions were submitted by each participant, all of the functions were entered into a spreadsheet, along with the user's anonymous identification numbers and the function identification numbers. Each of the 12 participants identified between 16 and 27 total functions for the portable music CD player. The average number of identified functions was 21. When the online applications were completed, the recorded functions were then entered into the spreadsheet to coincide with the initially identified functions. A complete analysis of the recorded functions could then be conducted. The recorded functions and evaluation data for the Functional Basis method and the Functional Description Template method are available in Appendix D5 and Appendix D6, respectively. The classification of the recorded functions for the Functional Description Template method is available in Appendix D7.

5.3.1 Expressiveness

The expressiveness of each method was measured by the total number of recorded terms that matched the user's original terms. Before discussing the total number of matching terms, the matches per functional statement are explored. In the Functional Basis method, functions were found to have between 0 and 3 matching terms, where the average number of matches per function was 0.29 terms. In the Functional Description Template, functions had between 0 and 5 matches, where the average was 1.70 matching terms per function, over five times greater than the Functional Basis method.

The total number of matching terms for each participant is shown in Table 3. In the Functional Basis method, for all of the functions recorded by each participant, the number of matching terms ranged from 1 term to 13 terms, with an average of 6 terms. In the Functional Template method, the number of matching terms for all of a participant's functions ranged from 18 to 56 terms, with an average of 35 terms. This measure indicates that using the Functional Description Template, the participants recorded an average of 29 more matched terms than they did with the Functional Basis method.

Table 3: Comparison of matched terms

User ID	Matched terms (FB)	Matched Terms (FDT)	Increased matches	Multiple of increase
101	8	56	48	7.00
102	6	37	31	6.17
103	6	45	39	7.50
104	7	31	24	4.43
201	13	30	17	2.31
202	6	35	29	5.83
203	1	29	28	29.00
205	1	30	29	30.00
302	10	32	22	3.20
305	1	36	35	36.00
306	10	42	32	4.20
307	2	18	16	9.00
Minimum	1	18	16	2.31
Maximum	13	56	48	36.00
Average	6	35	29	12.05

In addition to this average increase, it is important to note how many participants showed improved expressiveness using the Functional Description Template method. As shown in Table 3, all 12 participants in the study recorded more matching terms using the Functional Description Template method than they did using the Functional Basis method. The number of increased matches ranged from 16 to 48 terms. Due to the small number of matched terms in the functions recorded by the Functional Basis method, these additional matched terms showed a substantial improvement in expressiveness. The smallest improvement yielded 2.3 times as many matching terms and the largest improvement was by a participant who only was able to match one term using the Functional Basis method, but was able to match 36 terms using the Functional Description Template method. The average participant matched 12 times as many terms using the Functional Description Template method as compared to the Functional Basis method.

These results indicate that the Functional Description Template method allows the user to be far more expressive than does the Functional Basis method. The explanation for this improvement is found in two features of the Functional Description Template method. First, freeform text entry allows the user to enter terms from the original function. Second, offering numerous synonyms to the 30 action terms increases the chance that a user will locate the action term that was used in their original function.

5.3.2 Correctness

The number of correctly recorded functions indicates which method best allowed the user to record the intended meaning of the function while still selecting the correct terms. In a sense, the correctness measures the clarity and ease of use of the method. The results of this analysis are shown in Table 4.

Using the Functional Basis method, the participants recorded between 9 and 90 percent of their functions correctly, with an average of 51% of the functions being correctly recorded. Using the Functional Description Template method, the participants recorded between 43 and 100 percent of their functions correctly, with an average of 74 % of the functions being correctly recorded. These values indicate that using the Functional Description Template method resulted in a 23% average increase in correctness when compared to the Functional Basis method.

Table 4: Comparison of correct functions

		Functional Basis			Functional Description			
User ID	Functions	Correct	Partial	Incorrect	Correct	Partial	Incorrect	% Correct Increase
101	18	9	7	2	16	1	1	39
102	22	12	8	2	14	7	1	9
103	18	10	7	1	15	2	1	28
104	20	18	2	0	15	3	2	-15
201	27	16	8	3	13	5	9	-11
202	21	10	9	2	19	2	0	43
203	24	11	2	11	11	2	11	0
205	22	13	8	1	19	2	1	27
302	17	10	4	3	15	2	0	29
305	22	2	2	18	18	2	2	73
306	16	7	4	5	16	0	0	56
307	21	9	6	6	9	7	5	0
Min	16	2	2	0	9	0	0	-15
Max	27	18	9	18	19	7	11	73
Avg	21	11	6	5	15	3	3	23

In comparing the participant's success using each method, it was found that 8 out of 12 participants recorded functions with greater correctness using the Functional Description Template method than with the Functional Basis method. The largest improvement in correctness was 73%. Two of the participants performed equally well with each method and another two participants performed better using the Functional Basis method. Of the two participants that performed worse using the Functional Description Template method, one user (User 201), for some unknown reason, failed to record many of the original functions. These absent functions account for the small number of correct functions recorded by this user with the Functional Description Template method. Although the cause may not be clear, the results of this study indicate that the Functional Description Template method allowed users to record their functions more correctly. One possible explanation is that the user's found the bases of entity, property, and action terms to be clearer than those used in the Functional Basis method.

5.3.3 Information Loss

The amount of information lost when the functions were recorded is an indication of the method's ability to record complete functional descriptions. The results of this analysis are shown in Table 5, where the units are number of pieces of information lost (see Section 5.2). Using the Functional Basis method, participants were unable to record anywhere from 3 to 51 pieces of information from their functional descriptions, with an average loss of 18 pieces of information. Using the Functional Description Template, the amount of information lost for each participant ranged from 0 to 28 pieces of information, with an average of 11 pieces of information lost. Therefore, using the Functional Description Template method resulted in an average of 7 fewer pieces of information being lost when recording the functions as compared to the Functional Basis method.

Table 5: Comparison of information loss

User ID	Lost Information (FB)	Lost Information (FDT)	Decreased Information Loss
101	25	11	14
102	8	6	2
103	15	9	6
104	15	13	2
201	11	21	-10
202	3	0	3
203	36	28	8
205	5	4	1
302	13	0	13
305	51	20	31
306	26	10	16
307	6	8	-2
Minimum	3	0	-10
Maximum	51	28	31
Average	18	11	7

Comparing the recorded functions for each participant, 10 out of 12 participants lost more information using the Functional Basis method to record their functions than they did using the Functional Description Template method. The amount of improvement was as large as 31 fewer pieces of information being lost using the Functional Description Template method than using the Functional Basis method. For the two participants that lost more information using the Functional Description Template method, one participant only lost two additional pieces of information using this method and the other was User 201. As described in the evaluation of correctness, User 201 failed to record many functions using the Functional Description Template method, thus causing much information to be lost. The many participants that lost less information using the Functional Description Template method indicate that this method is better suited to record complete functional descriptions than the Functional Basis method. The explanation is that the Functional Description Template offers the user templates that allow for more complete functional statements to be recorded.

5.3.4 Categorization

The categorization of the recorded functions is an indication of how well the method can reduce the variability of the users' functions. The variability of the functional statements produced by the participants is quite clear. The participants were all asked to identify the functions for the same product, a portable music CD player. The 12 participants identified a total of 248 functions, which included 225 unique functions. The number of unique functions does not count functions that have a literal representation identical to that of another function. This large number of unique functions is due to the numerous

ways a single function can be represented by different individuals. For this reason, a means of categorizing the functions into a given functional language is preferable. However, the optimal level of categorization is unknown. A small reduction in the number of unique functions will still allow for great variability in the archived functions and too large of a reduction may eliminate or distort the user's intended meaning.

In this measure, the objective was to show that the Functional Description Template method could offer a similar level of categorization as the Functional Basis method. Using the Functional Basis method, the participants recorded a total of 210 functions, of which 139 were unique. Therefore, the Functional Basis method allowed for a 34% reduction in the number of functions that were recorded. Using the Functional Description Template method, the participants recorded a total of 220 functions, of which 145 were unique. This level of categorization yielded a 34% reduction in the number of recorded functions, the same amount as the Functional Basis method. Therefore, despite the changes made to the functional basis used in the Functional Description Template, the same amount of reduction in variability was obtained.

5.3.5 Ease of Use

The ease of use was measured by the user's preference between the two methods as determined by the evaluation form. The first question asked the participants which method was easier for locating the desired terms. The user's responses are shown in Figure 25.

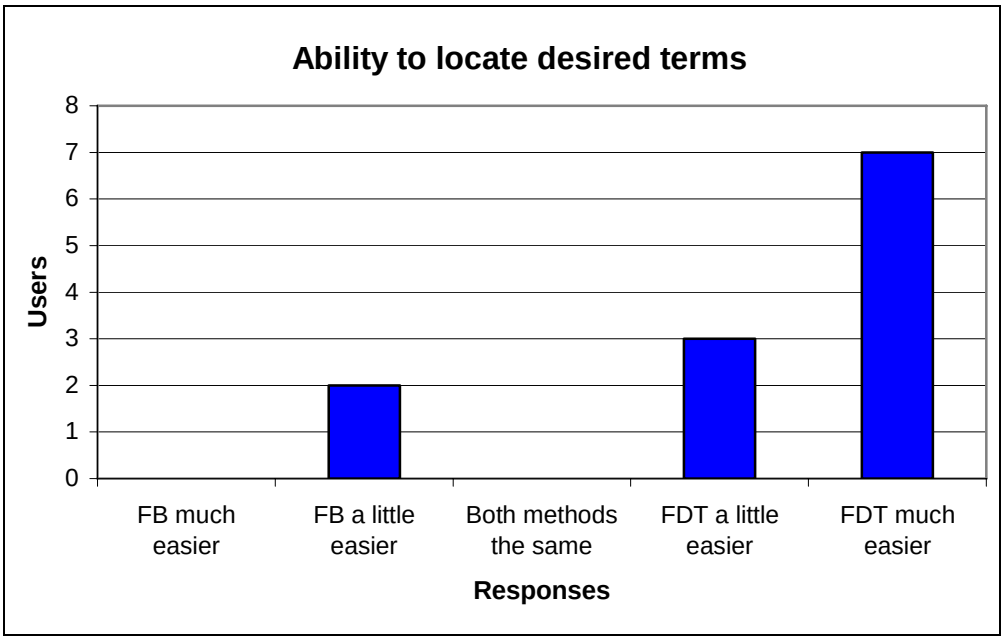


Figure 25: User responses to evaluation question #1

For this question, 10 out of 12 participants indicated that the Functional Description Template was easier to use and 7 of those participants felt that the method was much easier to use than the Functional Basis method. This result indicates a strong preference for the terms that are used in the Functional Description Template as well as the arrangement of those terms. The ease of locating the desired term can be a result of several factors: the use of common language terms, providing several synonyms for action terms, simplifying the hierarchy of entities and properties, and removing the hierarchy for action terms.

The second survey question asked the participants which method most accurately recorded their initial functions. The user's responses are shown in Figure 26.

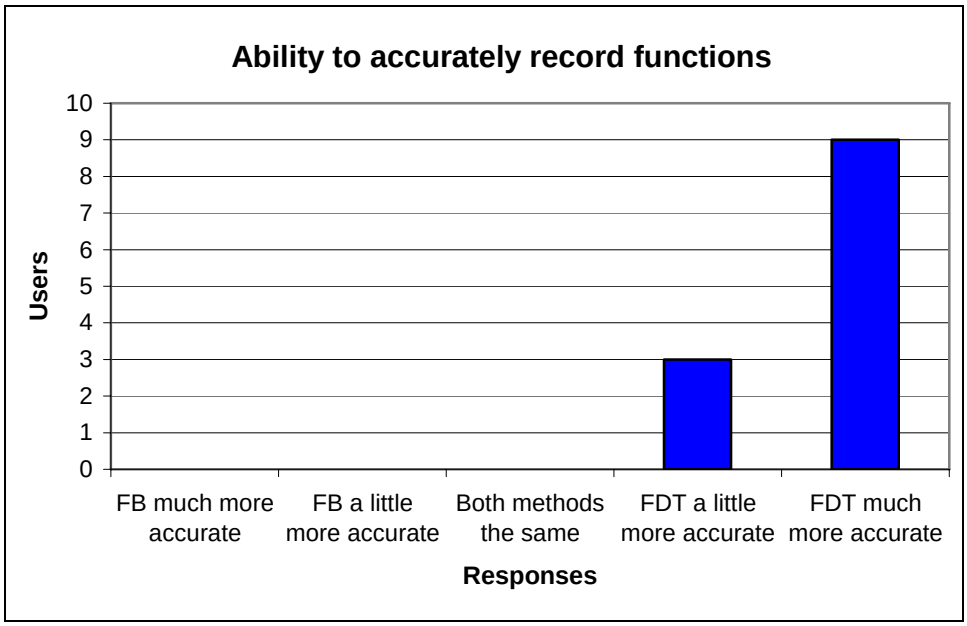


Figure 26: User responses to evaluation question #2

For this question, all 12 participants indicated that the Functional Description Template method was more accurate, and 9 of those 12 felt that the method was much more accurate when compared to the Functional Basis method. This strong response is a result of allowing the user to type in any terms for entities and properties and providing a large selection of action synonyms. The Functional Basis method requires users to select terms that are not found in their functions. Therefore, this method was not preferred by any of the participants.

Lastly, the participants were asked to add any comments that they had regarding the use of these two methods. Their responses illustrate their preference between the two methods, as well as their reasons. All of the user's responses are available in Appendix D8. Some of the positive responses regarding the Functional Description Template method are given below.

- "Template method is far superior to basis method. The only time I had trouble with the template was when a part of my decomposition was vague or poorly worded."

- "The description was far superior to the basis method; in fact I could not record most of my functions using the latter method."

- "Functional Description Template was much more descriptive and accurate. I could locate the functions easily as most of the functions that I used in my functional decomposition were available."

Some of the negative responses regarding the Functional Description Template method offer valuable suggestions for future improvement. Some of these comments are given below:

- "The Functional Description Template is approaching too many terms to be easily navigable to find the desired term."

- "Allow the user to indent and reorder and insert new FRs where they choose. Right now the only option is to add or remove, no edit."

- "FDT was overall easier to use than the FB, but the FDT action list was hard to use because it was not in alphabetical order."

- "I thought Functional Description was a bit easier, but it was still difficult to (or unable to) make certain statements such as "allow user to (verb)". It also seemed that more options were needed at times in the record functions segment to allow the user to make statements like using states and multiple entities like "convert state of data from electrical to acoustic."

Most of the negative responses regarding the Functional Basis method were similar and regarded the difficulty in locating terms. Some of these responses are given below.

- "I had a hard time figuring out where to find things in the Basis method."

- "I had trouble finding the exact words I was looking for in the basis version so I usually just compromised and picked something that I thought was close but usually felt that some of the meaning was lost by doing so."

These statements made by the participants reinforce the quantitative results that illustrate the improved expressiveness, completeness, and clarity of the Functional Description Template method. A summary of the results from this evaluation is given in Table 6.

Table 6: Summary of evaluation results

Measure	Units	FB	FDT	% users better with FDT
Expressiveness	Average matched terms	6	35	100
Correctness	Average percentage of correct functions	51	74	67
Information Loss	Average pieces of information lost	18	11	83
Categorization	Percent reduction in recorded functions	34	34	N/A
Ease of Use: Locating terms	Users who favored the method	2	10	83
Ease of Use: Recording functions accurately	Users who favored the method	0	12	100

5.3.6 Correlations

The correlation between the measures used in the evaluation may offer additional insight into how users benefit from using the Functional Description Template method. The three comparative measures that were calculated based upon the participants' recorded functions were expressiveness, correctness, and information loss. Therefore, the correlation between each of these measures will be discussed.

An analysis of expressiveness versus correctness and expressiveness versus information loss showed very little correlation between the two measures. For a linear correlation, the r-squared values for the two analyses were 0.35 and 0.32, respectively. Therefore, the participants' ability to express the terms in their original functions was not correlated to their ability to correctly and completely record those functions. This result is a logical outcome. The ability to correctly classify a term from a functional statement is irrespective of the terminology. A user may correctly classify a term, but not match their original term, or vice versa. Also, a user can retain more of the functional information, yet not match the terms.

However, an analysis between correctness and information loss did show a loose correlation. For a linear correlation, the r-squared value was 0.66. An r-squared value of 0.73 was obtained for a second order polynomial fit, as shown in Figure 27.

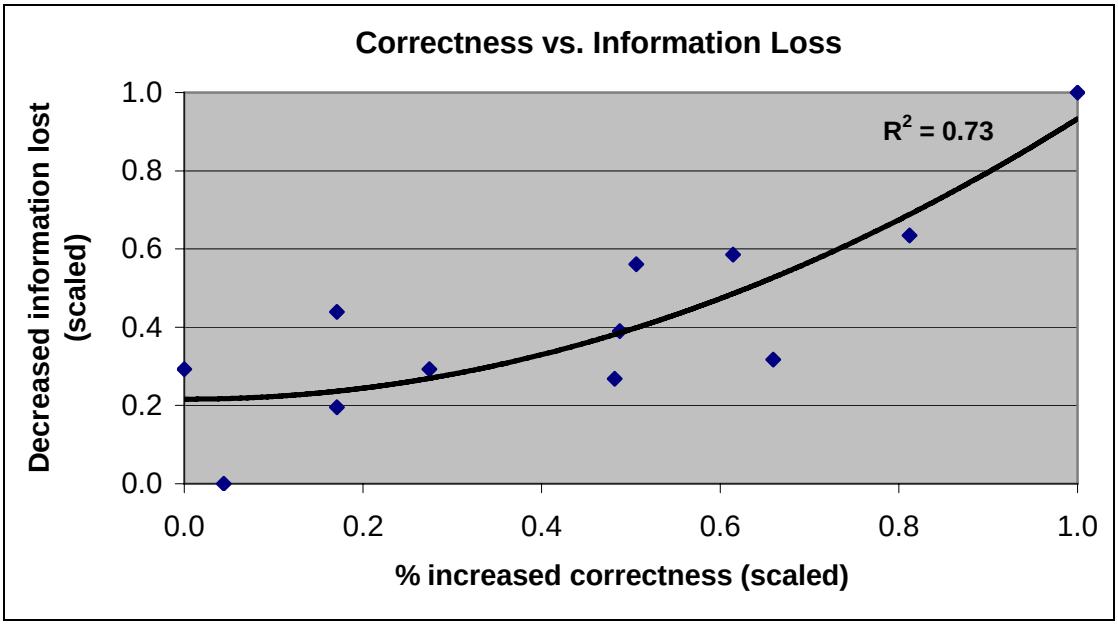


Figure 27: Correctness vs. Information Loss

In this plot, the results of the correctness and information loss measures have been scaled between 0 and 1. A correlation does appear to exist between the two measures and is confirmed by the r-squared value. Further testing with a larger sample size is necessary to evaluate the strength of this correlation. One explanation for this correlation is that both improved correctness and decreased information loss rely on a clear understanding of the Functional Description Template. A user who is able to select the correct terms for their functional statement is more likely to select a more descriptive template and fill in more of the original functional information. The measures were chosen to be independent of each other and therefore there is no inherent relation between correctness and information loss. In other words, a user may omit information from their original functions and still record all of their functions correctly if every recorded term accurately portrays the meaning of a term in their original function. Similarly, a user may incorrectly classify the terms in their functions, but retain all of the functional information. Therefore, the explanation for this correlation is that each of the two measures relies on the same skills of the user.

Chapter 6: Performing Search on the Repository

It is essential that the information stored in the repository be easily accessible to users in a straightforward manner and that a search of this information provide meaningful results. To accomplish this, the following three search tools have been proposed:

- Keyword search
- Category filter
- Function search

6.1 Keyword Search

The primary search tool that has been proposed is a keyword search, in which the user enters the desired search terms using freeform text entry. The user may enter multiple terms and may use AND/OR operators to conduct more specific searches. The user must also specify the search space in terms of which fields will be searched. The keyword search may be used to search any of the freeform text entry fields that were described earlier as well as the fields that record the functions of the product or concept. These fields are shown below in bold.

- Product Information
    - **Product name**
    - Product type
    - **Product description**
    - Development stage
    - **Applications**
- Biological Inspiration

    - **Biological name**
    - Biological type
    - **Biological description**
- Functions
- Resources
    - **Primary source**
    - **Additional references**
    - **Media**

In order to search any one of these fields, the user must check a box that indicates the inclusion of that field. Multiple fields may be selected, or the user may even check a box to indicate a search of all the fields. A screenshot of the keyword search section of the search form is shown in Figure 28.

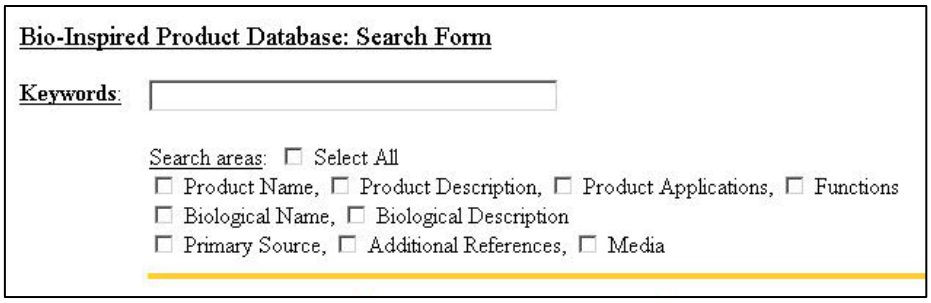


Figure 28: Search Form: Keyword search

The search is conducted by using a string matching algorithm that is a combination of two types of string matching algorithms; namely, equivalence method and similarity method. The equivalence method compares two strings and returns true or false

depending upon whether the strings match. The similarity method compares a given string to a set of strings and ranks those strings in order of similarity. This system uses a combination of equivalence and similarity methods to perform the keyword search on the repository of bio-inspired products and concepts.

6.2 Category Filter

The second proposed search tool is the category filter. This method of searching is designed to filter results based upon the fields that are recorded using menu selection. These fields are shown below in bold.

- Product Information
    - Product name
    - **Product type**
    - Product description
    - **Development stage**
    - Applications
- Biological Inspiration
    - Biological name
    - **Biological type**
    - Biological description
- Functions
- Resources
    - Primary source
    - Additional references

- Media

To filter results from the repository, the user may select entries from any of these categories. Multiple selections from each category are allowed, enabling the user to conduct a broader search. The search is conducted by using a string matching algorithm that uses an equivalence method to search for fields that have the same value that the user has selected. This search tool may be used in conjunction with the keyword search to filter the results, or it can be used independently to act as a way to browse the repository. For example, using the category filter, a user may browse all entries in the repository that were inspired by fish, or perhaps all entries that describe products that are currently available. A screenshot of the category section of the search form is shown in Figure 29.

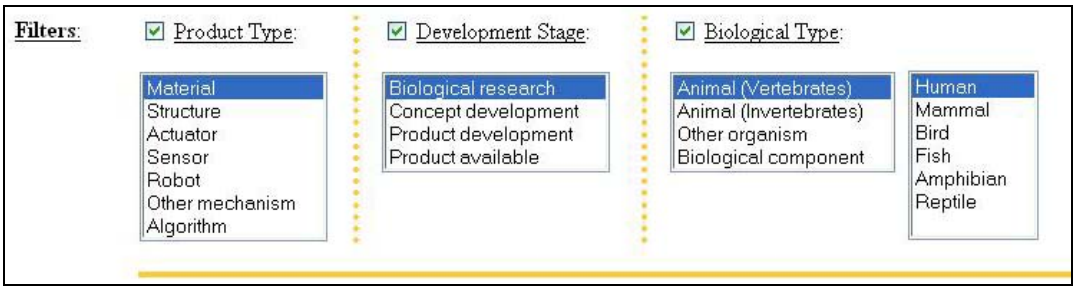


Figure 29: Search Form: Category filter

6.3 Function Search

The final proposed search tool is the function search. The function search is used to specifically search for products or concepts that meet a particular function or set of functions. While the keyword search may be used to search the functions of the products and concepts in the repository, the function search is specifically designed to search by function. This search tool aids the user in creating the functional statements for which to

search and conducts a more flexible search that returns more useful results. In order to search the repository using this method, the user forms functional statements to search for by using a modified version of the Functional Description Template. This version requires all terms to be chosen via menu selection. Without any freeform text entry, all search terms are chosen from the standardized lists of actions, entities, and properties.

The search is conducted by using an equivalence string matching algorithm and a scoring function to rank the results. The string matching is performed over several fields in the repository that are used for storing functions. For all functions that are recorded in the repository, several fields are filled that store the information about each function. This information includes all elements of the functional statement, as well as the classification of terms. For example, consider the function “propel vehicle through water”. In addition to storing this statement in a field in the repository, the terms “propel”, “device”, and “liquid” are stored to indicate the low level classification of these terms. The high level terms “move”, “artifact”, and “material” are also stored. Therefore, when a search is conducted on a functional statement, a string matching algorithm can match any of the low-level or high-level classifications of the terms.

Consider a user that is searching for a bio-inspired underwater vehicle. Using the Functional Description Template on the search form, the user may search for the function “propel object through liquid”. The search that is conducted will attempt to match these terms with terms that are used in functional statements that are stored in the repository. The search will also look for the terms in the high-level description “move artifact

through material". For results with the same high level action term, the search may return products that contain functional statements in any of the following forms:

- Propel object through liquid
- Propel object through material
- Propel object through ----
- Propel artifact through liquid
- Propel artifact through material
- Propel artifact through ----
- Propel ---- through liquid
- Propel ---- through material
- Propel ---- through ----
- Move object through liquid
- Move object through material
- Move object through ----
- Move artifact through liquid
- Move artifact through material
- Move artifact through ----
- Move ---- through liquid
- Move ---- through material
- Move ---- through ----

In the above list, the category terms (artifact, material, and move) imply that any term in that category is being used. For example, a product with the function "propel robot

through water” would match the function type “move artifact through liquid”. This search method is likely to return numerous results. Therefore, a scoring function is used to rank the strength of the results and display them in a ranked order. A function that matches all low-level terms will score the highest and a function that matches only a single high-level term will score the lowest. Currently, no consideration is given to prepositions or conjunctions. Any preposition or conjunction may be present in the functions that are searched. By using this method for the function search, the results should best match the function desired by the user.

6.4 Examples

In order to illustrate the type of searches that may be conducted and the results, two examples will be shown. Each example describes a design scenario and a search that may be conducted. The search tools that have been proposed have not yet been implemented and therefore only the expected top result from these searches can be shown, along with the information that is in the repository for that product.

6.4.1 Example 1

An engineer is designing an automated vehicle for the military that can be used for underwater reconnaissance. The engineer, familiar with the recent advances in bio-inspired engineering, decides to search the repository of bio-inspired products and concepts. The engineer may search for ideas using a combination of the search tools described above. In this case, a search is conducted for the keywords “underwater reconnaissance”, as well as the function “move device in liquid”. From this search, many

results are returned, some of which contain only the keyword “underwater” and some of which contain a variation of the function “move device in liquid”. However, the expected top result is one that describes an unmanned underwater vehicle that was inspired by the tuna [Ande99]. This entry in the repository contains the keyword “underwater” in the product description and contains the keyword “reconnaissance” in the applications. Furthermore, one of the product’s functions, “propel robot through water”, closely matches the search function. The user may then view the complete record for this entry in the repository, which is shown below.

Product Information

Product Name: VCUUV

Product Type: Robot

Product Description: An unmanned underwater vehicle with a low drag body and flexible hull. Uses vorticity control as a means for both propulsion and maneuvering. Also, uses caudal and pectoral fins for steering.

Development Stage: Product development

Applications: Mine reconnaissance, surveying, cable laying

Functions

Propel vehicle through water

Detect location of mines

Regulate velocity of vehicle

Biological Inspiration

Biological Name: Yellow fin Tuna

Biological Type: Animal: Fish

Biological Description: The tuna has a very streamlined body and is highly maneuverable. It can accelerate and decelerate rapidly and maneuver in tight spaces.

Resources

Primary Source: J.M. Anderson and P.A. Kerrebrock, "The Vorticity Control Unmanned Undersea Vehicle (VCUUV): Performance Results," *11th International Symposium on Unmanned Untethered Submersible Technology*, Draper Report No. P-3747, Durham, NH, August 1999.

Additional References: http://www.draper.com

Media:

6.4.2 Example 2

An engineer is designing a product and wishes to consider a new form of attachment for one of the components. Therefore, the engineer may search the repository of bio-inspired products and concept for ideas from nature on attachment. Suppose the engineer uses the function search and searches for "attach object to object". Of the many results that may be returned, the strongest match that is expected is that for Gecko tape, a new adhesive inspired by the attachment mechanism used on gecko's feet [Geim03]. The entry for this product contained a very close match to the search function, "connect item to object". The user is then able to view the complete record for this product, which is shown below.

Product Information

Product Name: Gecko tape

Product Type: Material

Product Description: Gecko tape is a material that is covered with millions of synthetic setae, or nanoscopic hairs. Each synthetic hair is made from a material called kapton and measures 2.0 microns in height and 0.2 microns in diameter - the same as gecko hairs. The hair-covered tape is made using a mold created by a lithographic process. A piece of tape one square centimeter holds around 100 million of these artificial setae and could support a weight of one kilogram.

Development Stage: Product development

Applications: Self-cleaning re-attachable adhesives, climbing robots

Functions

Adhere tape to surface of object

Connect item to object

Maintain adhesion of tape

Prevent adhesion of dirt

Support weight of object

Biological Inspiration

Biological Name: Gecko

Biological Type: Animal: Reptile

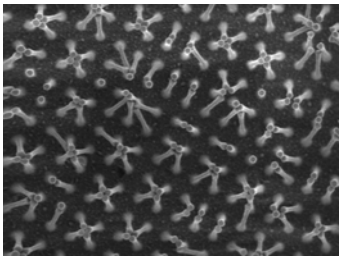
Biological Description: The soles of Gecko feet have sticky ridges called lamellae. The ridges of each foot contain half a million hairs, called setae. The end of each hair splits into between 100 and 1,000 tiny spatulas, visible only with an electron microscope. The ultra-close contact of the split ends with a wall or floor creates billions of weak molecular attractions called van der Waals forces. This offers incredibly strong, dry adhesion that is also immediately reversible - at a certain angle the ends automatically detach and roll up.

Resources

Primary Source: A.K. Geim, S.V. Dubonos, I.V. Grigorieva, K.S. Novoselov, A.A. Zhukov and S.Yu. Shapoval, "Microfabricated Adhesive Mimicking Gecko Foot-Hair," *Nature Materials*, 2003, Vol. 2, pp. 461-463. [Geim03]

Additional References: http://www.lclark.edu/~autumn/climbing/climb.html [Autu00]

Media:



Chapter 7: Conclusions

7.1 Contributions

The work presented in this thesis offers the following three contributions toward locating a source of bio-inspiration for product development:

1. Repository of bio-inspired product concepts
2. Functional Description Template
3. Proposed search tools

First, a repository of bio-inspired products and concepts was created that contains detailed information about existing products in various stages of development and biological systems that may provide new design concepts. Furthermore, the functions of these products and concepts were archived into the repository.

Next, the Functional Description Template was developed that allows users to quickly and easily enter functions into the repository while retaining a natural language form. This method of archiving functions is applicable to all classes of products as well as biological systems. As demonstrated in an evaluation, the Functional Description Template allowed greater expressiveness and completeness in the user's recorded functional statements when compared to the Functional Basis method, while still offering the same reduction in variability of the recorded functions. All 12 participants in the study recorded more matched terms using the Functional Description Template method, averaging an increase of 29 matched terms, 12 times as many as were recorded using the Functional Basis method. Also, 10 of the 12 participants lost less functional information

using the Functional Description Template method, averaging 7 fewer pieces of information lost than with the Functional Basis method. Measuring the categorization of functions in each method showed that the Functional Description Template method provided the same 34% reduction in the variability of recorded functions as the Functional Basis method. The evaluation also indicated that the Functional Description Template method was easier to use than the Functional Basis method. There was an average increase of 23% in the number of correct functions recorded and 8 of the 12 participants showed improvement. Also, the user evaluations indicated that 10 of the 12 participants thought that locating terms was easier in the Functional Description Template and all of the users thought that the method could more accurately record their functions.

Third, three search tools were proposed that are easy to use and can accurately retrieve the desired information from the repository. The search tools allow for a keyword search of the information in the repository as well as a filtering by certain categories. The function search allows users to search for products that satisfy functions of similar meaning, but are stated with different terminology. These search tools are flexible and allow for a content-based search of the repository.

7.2 Anticipated Benefits

The design tool that is formed by these three contributions offers great benefits to the engineering community. The repository, when populated with a growing number of products and concepts, will make knowledge of bio-inspired ideas more accessible to

engineers. This readily accessible information can lead to the development of new and innovative products. Additionally, the repository and Functional Description Template are not limited to archiving bio-inspired products and concepts. In time, the repository could be used to archive any product or design concept and offer a more complete knowledge base for engineers seeking candidate design concepts. Another benefit of this work is that biological systems can now be easily indexed and searched by function. In a sense, a functional decomposition of nature can now be performed and engineers can search nature by function.

7.3 Future Work

While the system discussed in this paper offers many new features and benefits, there is still additional work that is possible. In terms of the repository, adding more products and concepts is clearly essential to improving the potential of the system. Since much of the Functional Description Template is extensible, the scope of the language could be improved if more synonyms and troponyms were added to the action terms and if more properties were added. Another potential improvement to the template would be to allow for adverbs to be used. However, this would have to be done without further complicating the process of recording a functional statement. Ease-of-use is an important attribute of the system. A final improvement to the Functional Description Template would be the addition of more possible sentence templates, perhaps allowing for more than two entities to be used. As for the proposed search tools, future work must be done to implement these tools into the use of the repository. Once the search methods that have been proposed are functional, additional features may be added. One such feature may be to

allow users to customize the search priorities that are used to return results in the function search. Users may want to decide themselves whether the action term, entity term, or property term is most relevant. Another possible feature that could be implemented is user customization of the visualization of the results. Such a feature would allow the user to determine which fields are presented in the search results and in what order. However, the goal of any of this future work must make bio-inspiration an easy and appealing design method for engineers working in product development.

Appendices

Appendix A: Repository of Bio-inspired Products

Appendix A1: Archived Products and Biological Inspiration

ProductID	ProductName	ProductType	BiologicalName	BiologicalType1	BiologicalType2
1	Electroactive polymers	Actuator	Human	Animal (Vertebrate)	Human
2	McKibben artifical muscles	Actuator	Human	Animal (Vertebrate)	Human
3	Smart gel actuator	Actuator	Worms	Animal (Invertebrate)	Worms
4	Active thermal insulation	Material	Penguin	Animal (Vertebrate)	Bird
5	Adaptive camoflauge	Material	Cuttlefish	Animal (Vertebrate)	Fish
6	Artificial spider silk	Material	Spider	Animal (Invertebrate)	Insects, spiders, and crustaceans
7	Insect repellant apparel	Material	Chrysanthemum	Other Organism	Plant
8	Cermaic coating	Material	Horse	Animal (Vertebrate)	Mammal
9	Fibrous composite	Material	Wood	Other Organism	Plant
10	Lubricant	Material	Slug	Animal (Invertebrate)	Mollusks
11	Natural fiber composite	Material	Flax and hemp	Other Organism	Plant
12	Reflective material	Material	Bobtail squid	Animal (Invertebrate)	Mollusks
13	Self-cleaning paint	Material	Lotus plant	Other Organism	Plant
14	Speedo fastskin suit	Material	Shark	Animal (Invertebrate)	Fish
15	Surface coating technology	Material	Proteins	Biological component	Protein
16	Gecko tape	Material	Gecko	Animal (Vertebrate)	Reptile
17	Frog glue	Material	Frog	Animal (Vertebrate)	Amphibian
18	Underwater adhesive	Material	Blue mussel	Animal (Invertebrate)	Mollusks
19	Fog collecting structure	Structure	Desert beetle	Animal (Invertebrate)	Insects, spiders, and crustaceans
20	Photonic crystal fibers	Material	Sea mouse	Animal (Invertebrate)	Worms
21	Biological motor	Mechanism	E. coli bacteria	Other organism	Prokaryote
22	Bipedal robots	Robot	Human	Animal (Vertebrate)	Human
23	Cockroach robots	Robot	Cockroach	Animal (Invertebrate)	Insects, spiders, and crustaceans
24	Cricket robot	Robot	Cricket	Animal (Invertebrate)	Insects, spiders, and crustaceans
25	Entomopter	Robot	Hawk moth	Animal (Invertebrate)	Insects, spiders, and crustaceans

ProductID	ProductName	ProductType	BiologicalName	BiologicalType1	BiologicalType2
26	Bird robot	Robot	Hummingbird	Animal (Vertebrate)	Bird
27	Frog robot	Robot	Frog	Animal (Vertebrate)	Amphibian
28	Gecko robot	Robot	Gecko	Animal (Vertebrate)	Reptile
29	Lamprey robot	Robot	Lamprey and eel	Animal (Vertebrate)	Fish
30	Lobster robot	Robot	Lobster	Animal (Invertebrate)	Insects, spiders, and crustaceans
31	Microbat	Robot	Bats	Animal (Vertebrate)	Mammal
32	Micromechanical flying insect	Robot	Blowfly Calliphora	Animal (Invertebrate)	Insects, spiders, and crustaceans
33	Robopike	Robot	Pike	Animal (Vertebrate)	Fish
34	Robotic rodent	Robot	Rat	Animal (Vertebrate)	Mammal
35	Robotuna	Robot	Tuna	Animal (Vertebrate)	Fish
36	Scorpion robot	Robot	Scorpion	Animal (Invertebrate)	Insects, spiders, and crustaceans
37	Snake robots	Robot	Snake	Animal (Vertebrate)	Reptile
38	Visual Odometer	Sensor	Insects	Animal (Invertebrate)	Insects, spiders, and crustaceans
39	Tuna robot	Robot	Tuna	Animal (Vertebrate)	Fish
40	Intelligent hearing aid	Sensor	Human	Animal (Vertebrate)	Human
41	Face recognition	Algorithm	Human	Animal (Vertebrate)	Human
42	Leak sealing system	Mechanism	Human	Animal (Vertebrate)	Human
43	Foveal vision camera system	Mechanism	Human	Animal (Vertebrate)	Human
44	Polymer-surface recognition	Mechanism	Proteins	Biological component	Protein
45	Pulse combustion	Mechanism	Bombadier beetle	Animal (Invertebrate)	Insects, spiders, and crustaceans
46	Artificial sensory hand	Robot	Human	Animal (Vertebrate)	Human
47	Artificial muscle spindle	Sensor	Human	Animal (Vertebrate)	Human
48	Artificial sensory head	Sensor	Human	Animal (Vertebrate)	Human
49	Acoustic pressure sensor	Sensor	Fly	Animal (Invertebrate)	Insects, spiders, and crustaceans
50	Micromechanical cochlea	Sensor	Human	Animal (Vertebrate)	Human
51	RoBat	Sensor	Bat	Animal (Vertebrate)	Mammal
52	Sound localization model	Sensor	Barn owl	Animal (Vertebrate)	Bird
53	Haircell sensor	Sensor	Fish	Animal (Vertebrate)	Fish
54	Infrared sensor	Sensor	Jewel beetle	Animal (Invertebrate)	Insects, spiders, and crustaceans
55	Strain sensor	Sensor	Insects	Animal (Invertebrate)	Insects, spiders, and crustaceans
56	Electronic nose	Sensor	Human	Animal (Vertebrate)	Human
57	Electronic tounge	Sensor	Human	Animal (Vertebrate)	Human
58	Odor Detection	Sensor	Human	Animal (Vertebrate)	Human

ProductID	ProductName	ProductType	BiologicalName	BiologicalType1	BiologicalType2
59	Analog VLSI motion sensor	Sensor	Fly	Animal (Invertebrate)	Insects, spiders, and crustaceans
60	Omnidirectional array sensors	Sensor	Insects	Animal (Invertebrate)	Insects, spiders, and crustaceans
61	Neuromorphic eye	Sensor	Fly	Animal (Invertebrate)	Insects, spiders, and crustaceans
62	Silicon retina	Sensor	Primates	Animal (Vertebrate)	Mammal
63	Polarized difference imaging	Sensor	Animals	Animal (Vertebrate)	Mammal
64	Vision algorithms	Algorithm	Human	Animal (Vertebrate)	Human
65	Holographic memory	Structure	Bacteriorhodopsin	Other organism	Prokaryote
66	Barbed wire	Structure	Plants	Other Organism	Plant
67	Biodegradeable compact discs	Structure	Corn	Other Organism	Plant
68	Biomimetic bipolar plates	Structure	Plant tissues	Other Organism	Plant
69	Birdman suit	Structure	Birds	Animal (Vertebrate)	Bird
70	Cambered wings	Structure	Birds	Animal (Vertebrate)	Bird
71	Diffraction gratings	Structure	Butterfly wings	Animal (Invertebrate)	Insects, spiders, and crustaceans
72	Fiber optics	Structure	Glass sponge	Animal (Invertebrate)	Sponges
73	Fibrous tubes	Structure	Bamboo	Other Organism	Plant
74	Bicycle crank arm	Structure	Human	Animal (Vertebrate)	Human
75	Ice axe	Structure	Woodpecker	Animal (Vertebrate)	Bird
76	Interferometric modulator	Structure	Peacock wings	Animal (Vertebrate)	Bird
77	NASA smartwing	Structure	Birds	Animal (Vertebrate)	Bird
78	Saw chain	Structure	Timber beetle larva	Animal (Invertebrate)	Insects, spiders, and crustaceans
79	Goat-tech soles	Structure	Goat feet	Animal (Vertebrate)	Mammal
80	Polygonal foldable membranes	Structure	Tree leaves	Other Organism	Plant
81	Slotted wing tips	Structure	Bird wings	Animal (Vertebrate)	Bird
82	Artificial pinna	Structure	Bat	Animal (Vertebrate)	Mammal
83	Velcro	Structure	Plant burrs	Other Organism	Plant
84	Responsive clothing	Material	Pine cones	Other Organism	Plant
85	Office heating/cooling	Structure	Termite mounds	Animal (Invertebrate)	Insects, spiders, and crustaceans
86	Aerospace structures	Structure	Horse	Animal (Vertebrate)	Mammal
87	Platinum nanostructures	Structure	Proteins	Biological component	Protein
88	Concept car	Structure	Boxfish	Animal (Vertebrate)	Fish
89	TransPhibian	Robot	Turtle	Animal (Vertebrate)	Reptile

Appendix A2: Functions of Archived Products

FunclD	ProductID	Function
1	1	Actuate motion of device
2	1	Regulate length of actuator
3	1	Receive electrical energy from power source
4	1	Convert electrical energy into mechanical energy
5	2	Actuate motion of device
6	2	Regulate length of actuator
7	2	Receive compressed air
8	2	Expand volume of tube
9	3	Actuate motion of device
10	3	Contain gel inside a structure
11	3	Control shape of gel
12	3	Expand gel
13	3	Contract gel
14	4	Retain heat
15	4	Maintain temperature of body
16	4	Expel water from material
17	5	Change color of material
18	5	Mimic color of environment
19	5	Redirect light
20	6	Increase strength of wire
21	6	Resist tension force in wire
22	6	Allow elongation of wire
23	6	Allow biodegradation of wire
24	7	Block insects
25	7	Integrate repellant into clothing
26	7	Eliminate odor of repellant
27	8	Increase strength of ceramic
28	8	Resist fracture of ceramic
29	8	Bond ceramic to bone
30	9	Increase strength of composite
31	9	Increase toughness of composite

FuncID	ProductID	Function
32	9	Bond reinforcing fiber to corrugated paperboard
33	10	Allow motion of slug
34	10	Reduce friction force on slug
35	10	Reduce friction coefficient of slug
36	11	Offer specific stiffness of fibers
37	11	Prevent compression failure of fibers
38	11	Retain shape of original structure
39	12	Redirect light using proteins
40	12	Redirect luminescence of bacteria
41	12	Control color of body
42	13	Remove dirt from walls
43	13	Restrict water from walls
44	13	Reduce friction coefficient of walls
45	14	Increase speed of swimmer
46	14	Reduce drag force on swimmer
47	14	Reduce friction coefficient of swimsuit
48	15	Immobilize proteins
49	15	Couple polymer to molecules
50	15	Attach proteins to substrate
51	16	Adhere tape to surface
52	16	Remove tape from surface
53	16	Support weight of object
54	17	Connect knee cartilage
55	17	Absorb force on glue
56	17	Increase hardness of glue
57	17	Provide porosity of glue
58	18	Attach glue to surface
59	18	Increase strength of glue
60	18	Resist water
61	19	Extract water from fog
62	19	Pull water to surface
63	19	Collect water
64	20	Redirect light

FuncID	ProductID	Function
65	20	Transmit light
66	21	Move device through body
67	21	Rotate flagellum
68	21	Convert food to chemical energy
69	21	Dispense drugs to cells
70	22	Move robot over land
71	22	Conserve energy of robot
72	22	Stabilize motion of robot
73	23	Move robot over land
74	23	Stabilize motion of robot
75	23	Navigate robot through obstacles
76	23	Regulate velocity of robot
77	24	Move robot over land
78	24	Stabilize motion of robot
79	24	Navigate robot through obstacles
80	24	Regulate velocity of robot
81	25	Propel robot through air
82	25	Generate lifting force on wings
83	25	Regulate velocity of wings
84	26	Propel robot through air
85	26	Generate lifting force on wings
86	26	Regulate velocity of wings
87	27	Move robot over land
88	27	Orient position of robot
89	27	Launch robot over obstacles
90	28	Move robot over land
91	28	Move robot up walls
92	28	Adhere robot to surface
93	29	Propel robot through water
94	29	Undulate body of robot
95	29	Control direction of robot
96	30	Move robot over land
97	30	Move robot in water

FuncID	ProductID	Function
98	30	Regulate velocity of robot
99	31	Propel robot through air
100	31	Generate lifting force on wings
101	31	Regulate velocity of wings
102	32	Propel robot through air
103	32	Generate lifting force on wings
104	32	Regulate velocity of wings
105	33	Propel robot through water
106	33	Undulate body of robot
107	33	Control direction of robot
108	34	Move robot over land
109	34	Stabilize motion of robot
110	34	Navigate robot through obstacles
111	34	Regulate velocity of robot
112	35	Propel robot through water
113	35	Undulate body of robot
114	35	Control direction of robot
115	36	Move robot over land
116	36	Stabilize motion of robot
117	36	Navigate robot through obstacles
118	36	Regulate velocity of robot
119	37	Move robot over land
120	37	Undulate body of robot
121	37	Navigate robot through obstacles
122	38	Navigate robot
123	38	Stabilize motion of robot
124	38	Detect motion of objects
125	38	Estimate distance of path
126	39	Propel robot through water
127	39	Undulate body of robot
128	39	Control direction of robot
129	39	Regulate velocity of robot
130	40	Locate sound

FuncID	ProductID	Function
131	40	Extract sound from noise
132	40	Receive sound
133	40	Process auditory signal
134	41	Recognize face
135	41	Measure face
136	41	Process measurements of face
137	41	Compare face to face
138	42	Detect crack in pipe
139	42	Detect leaking of fluid
140	42	Stop leaking of fluid
141	42	Move material into crack
142	42	Contain fluid
143	43	Detect object
144	43	Track position of object
145	43	Increase field of view of camera
146	43	Reduce image data
147	44	Recognize pattern of surface
148	44	Bind polymer to surface
149	45	Discharge boiling liquid
150	45	Increase pressure of liquid
151	45	Increase velocity of liquid
152	46	Apply force on object
153	46	Lift object with hand
154	46	Detect force on fingers
155	46	Detect angle of fingers
156	47	Move object
157	47	Adjust length of spindle
158	47	Apply force on sensor
159	47	Detect strain on sensor
160	48	See object
161	48	Detect taste of substance
162	48	Smell odor of substance
163	48	Hear sound from object

FuncID	ProductID	Function
164	49	Detect sound
165	49	Determine location of sound
166	49	Minimize size of processor
167	50	Detect sound
168	50	Process acoustic data
169	51	Detect motion of object
170	51	Detect trajectory of objects
171	51	Detect doppler shift of sound
172	52	Detect sound
173	52	Determine location of sound
174	53	Detect motion of fluid
175	53	Detect displacement of beam
176	53	Convert mechanical energy into electrical signal
177	54	Detect infrared radiation
178	54	Absorb thermal radiation
179	54	Detect expansion of sensor
180	55	Detect flow of air
181	55	Detect deformation of exoskeleton
182	55	Amplify strain of exoskeleton
183	56	Detect odor of substance
184	56	Distinguish substance from mixture
185	57	Taste water
186	57	Receive water
187	57	Determine chemicals in water
188	58	Recognize odor of substance
189	58	Detect concentration of vapor
190	58	Aggregate data from sensors
191	59	Detect light
192	59	Estimate motion of fly
193	59	Navigate fly through air
194	60	Detect motion of object
195	60	Detect light
196	60	Vary field of view of sensor

FuncID	ProductID	Function
197	61	Control motion of robot
198	61	Detect motion of terrain
199	61	Measure optic flow of terrain
200	62	Track motion of objects
201	62	See objects
202	62	Process data
203	63	Detect polarization of light
204	63	Enhance visibility of objects
205	63	See objects in scattering media
206	63	Enhance contrast of objects
207	64	Detect light
208	64	Distinguish intensity of light
209	64	Distinguish color of object
210	65	Store data with molecules
211	65	Absorb light
212	65	Change shape of molecule
213	65	Change color of molecule
214	66	Contain animals
215	66	Restrict people
216	66	Protect area of land
217	67	Store data on disc
218	67	Allow biodegradation of disc
219	68	Increase power of fuel cells
220	68	Allow motion of gas
221	68	Distribute gas through capillaries
222	69	Move human though air
223	69	Generate lifting force on wings
224	69	Direct flow of air
225	69	Control motion of human
226	70	Increase lifting force on wing
227	70	Control velocity of air
228	70	Control pressure of air
229	71	Display color of surface

FuncID	ProductID	Function
230	71	Increase viewing angle of light
231	71	Convert white light into blue light
232	72	Allow bending of fiber optics
233	72	Resist fracture of fiber optics
234	72	Increase strength of fiber optics
235	72	Transmit light though glass
236	72	Redirect light
237	73	Increase strength of tube
238	73	Resist fracture of tube
239	73	Provide bending stiffness to tube
240	74	Support weight of cyclist
241	74	Transfer force from cyclist
242	74	Resist fracture of crank arm
243	75	Hold axe in ice
244	75	Prevent motion of axe
245	75	Resist fracture of axe
246	76	Display color of surface
247	76	Cause interference of light
248	76	Redirect light
249	77	Generate lifting force on wing
250	77	Regulate lifting force on wing
251	77	Change shape of wing
252	77	Allow bending of wing
253	78	Separate wood
254	78	Remove wood from tree
255	78	Reduce force on chain
256	79	Support weight of human
257	79	Reduce force on foot
258	79	Increase friction coefficient of shoe
259	80	Contain structure
260	80	Reduce size of folded structure
261	80	Expand size of structure
262	80	Deploy structure

FuncID	ProductID	Function
263	81	Reduce drag force on wing
264	81	Decrease friction coefficient of wing
265	81	Change shape of wing
266	81	Vary height of wing tips
267	81	Allow bending of wing tips
268	82	Receive sound
269	82	Redirect sound
270	82	Detect location of sound
271	83	Attach velcro to object
272	83	Fasten object to object
273	83	Separate velcro
274	84	Detect humidity of skin
275	84	Allow bending of flaps
276	84	Open flaps
277	84	Close flaps
278	85	Regulate temperature of office
279	85	Regulate motion of air
280	85	Regulate temperature of air
281	85	Guide air
282	86	Increase strength of structure
283	86	Decrease weight of structure
284	86	Distribute force on structure
285	86	Resist fracture of structure
286	87	Control structure of platinum
287	87	Control size of nanostructures
288	88	Reduce drag force on car
289	88	Decrease friction coefficient of car
290	88	Allow motion of air
291	89	Move robot through water
292	89	Maintain direction of vehicle
293	89	Move robot on land
294	89	Rotate robot

Appendix A3: Function Classifications for Archived Products

FuncID	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	PropertyType
1	Start	Actuate	Artifact	Device			Motion	Motion
2	Change	Regulate	Artifact	Device			Length	Geometric
3	Acquire	Receive	Energy	Electrical	Artifact	Device		
4	Change	Convert	Energy	Electrical	Energy	Mechanical		
5	Start	Actuate	Artifact	Device			Motion	Motion
6	Change	Regulate	Artifact	Device			Length	Geometric
7	Acquire	Receive	Material	Gas				
8	Increase	Expand	Artifact	Object			Volume	Geometric
9	Start	Actuate	Artifact	Device			Motion	Motion
10	Contain	Contain	Material	Liquid	Artifact	Object		
11	Change	Control	Material	Liquid			Shape	Geometric
12	Increase	Expand	Material	Liquid				
13	Decrease	Contract	Material	Liquid				
14	Contain	Retain	Energy	Thermal				
15	Maintain	Maintain	Living entity	Organism: Human			Temperature	Thermo-physical
16	Eject	Expel	Material	Liquid	Material	Solid		
17	Change	Change	Material	Solid			Color	Material
18	Copy	Mimic	Space	Space			Color	Material
19	Guide	Redirect	Wave	Electromagnetic				
20	Increase	Increase	Material	Solid			Strength	Material
21	Stop	Resist	Material	Solid			Tension force	Mechanics
22	Provide	Allow	Material	Solid			Elongation	Motion
23	Provide	Allow	Material	Solid			Biodegradation	Chemical
24	Stop	Block	Living entity	Organism: Animal				
25	Mix	Integrate	Material	Liquid	Material	Solid		
26	Destroy	Eliminate	Material	Liquid			Odor	Chemical
27	Increase	Increase	Material	Solid			Strength	Material
28	Stop	Resist	Material	Solid			Fracture	Failure
29	Connect	Bond	Material	Solid	Material	Solid		
30	Increase	Increase	Material	Mixture			Strength	Material
31	Increase	Increase	Material	Mixture			Toughness	Material

FuncID	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	PropertyType
32	Connect	Bond	Material	Solid	Material	Solid		
33	Provide	Allow	Living entity	Organism: Animal			Motion	Motion
34	Decrease	Reduce	Living entity	Organism: Animal			Friction force	Mechanics
35	Decrease	Reduce	Living entity	Organism: Animal			Friction coefficient	Material
36	Provide	Offer	Material	Solid			Specific stiffness	Material
37	Stop	Prevent	Material	Solid			Compression	Failure
38	Maintain	Retain	Artifact	Object			Shape	Geometric
39	Guide	Redirect	Wave	Electromagnetic	Living entity	Protein		
40	Guide	Redirect	Living entity	Organism:			Luminescence	Material
41	Change	Control	Living entity	Organism: Animal			Color	Material
42	Remove	Remove	Material	Solid	Material	Solid		
43	Stop	Restrict	Material	Liquid	Material	Solid		
44	Decrease	Reduce	Material	Solid			Friction coefficient	Material
45	Increase	Increase	Living entity	Organism: Human			Speed	Motion
46	Decrease	Reduce	Living entity	Organism: Human			Drag force	Mechanics
47	Decrease	Reduce	Material	Solid			Friction coefficient	Material
48	Stop	Immobilize	Living entity	Protein				
49	Connect	Couple	Material	Solid	Particle	Molecule		
50	Connect	Attach	Living entity	Protein	Material	Solid		
51	Connect	Adhere	Material	Solid	Material	Solid		
52	Remove	Remove	Material	Solid	Material	Solid		
53	Secure	Support	Artifact	Object			Weight	Mechanics
54	Connect	Connect	Material	Solid				
55	Receive	Absorb	Material	Liquid			Force	Mechanics
56	Increase	Increase	Material	Liquid			Hardness	Material
57	Provide	Provide	Material	Liquid			Porosity	Material
58	Connect	Attach	Material	Liquid	Material	Solid		
59	Increase	Increase	Material	Liquid			Strength	Material
60	Stop	Resist	Material	Liquid				
61	Remove	Extract	Material	Liquid	Material	Gas		
62	Move	Pull	Material	Liquid	Material	Solid		
63	Collect	Collect	Material	Liquid				
64	Guide	Redirect	Wave	Electromagnetic				

FuncID	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	PropertyType
65	Move	Transmit	Wave	Electromagnetic				
66	Move	Move	Artifact	Device	Living entity	Organism: Human		
67	Rotate	Rotate	Living entity	Organ				
68	Change	Convert	Material	Solid	Energy	Chemical		
69	Provide	Dispense	Material	Solid	Living entity	Cell		
70	Move	Move	Artifact	Device	Material	Solid		
71	Maintain	Conserve	Artifact	Device			Energy	Mechanics
72	Maintain	Stabilize	Artifact	Device			Motion	Motion
73	Move	Move	Artifact	Device	Material	Solid		
74	Maintain	Stabilize	Artifact	Device			Motion	Motion
75	Guide	Navigate	Artifact	Device	Artifact	Object		
76	Change	Regulate	Artifact	Device			Velocity	Motion
77	Move	Move	Artifact	Device	Material	Solid		
78	Maintain	Stabilize	Artifact	Device			Motion	Motion
79	Guide	Navigate	Artifact	Device	Artifact	Object		
80	Change	Regulate	Artifact	Device			Velocity	Motion
81	Move	Propel	Artifact	Device	Material	Gas		
82	Create	Generate	Artifact	Object			Lifting force	Mechanics
83	Change	Regulate	Artifact	Object			Velocity	Motion
84	Move	Propel	Artifact	Device	Material	Gas		
85	Create	Generate	Artifact	Object			Lifting force	Mechanics
86	Change	Regulate	Artifact	Object			Velocity	Motion
87	Move	Move	Artifact	Device	Material	Solid		
88	Guide	Orient	Artifact	Device			Position	Motion
89	Move	Launch	Artifact	Device	Artifact	Object		
90	Move	Move	Artifact	Device	Material	Solid		
91	Move	Move	Artifact	Device	Material	Solid		
92	Connect	Adhere	Artifact	Device	Material	Solid		
93	Move	Propel	Artifact	Device	Material	Liquid		
94	Move	Undulate	Artifact	Object				
95	Change	Control	Artifact	Device			Direction	Motion
96	Move	Move	Artifact	Device	Material	Solid		
97	Move	Move	Artifact	Device	Material	Liquid		

FuncID	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	PropertyType
98	Change	Regulate	Artifact	Device			Velocity	Motion
99	Move	Propel	Artifact	Device	Material	Gas		
100	Create	Generate	Artifact	Object			Lifting force	Mechanics
101	Change	Regulate	Artifact	Object			Velocity	Motion
102	Move	Propel	Artifact	Device	Material	Gas		
103	Create	Generate	Artifact	Object			Lifting force	Mechanics
104	Change	Regulate	Artifact	Object			Velocity	Motion
105	Move	Propel	Artifact	Device	Material	Liquid		
106	Move	Undulate	Artifact	Object				
107	Change	Control	Artifact	Device			Direction	Motion
108	Move	Move	Artifact	Device	Material	Solid		
109	Maintain	Stabilize	Artifact	Device			Motion	Motion
110	Guide	Navigate	Artifact	Device	Artifact	Object		
111	Change	Regulate	Artifact	Device			Velocity	Motion
112	Move	Propel	Artifact	Device	Material	Liquid		
113	Move	Undulate	Artifact	Object				
114	Change	Control	Artifact	Device			Direction	Motion
115	Move	Move	Artifact	Device	Material	Solid		
116	Maintain	Stabilize	Artifact	Device			Motion	Motion
117	Guide	Navigate	Artifact	Device	Artifact	Object		
118	Change	Regulate	Artifact	Device			Velocity	Motion
119	Move	Move	Artifact	Device	Material	Solid		
120	Move	Undulate	Artifact	Object				
121	Guide	Navigate	Artifact	Device	Artifact	Object		
122	Guide	Navigate	Artifact	Device				
123	Maintain	Stabilize	Artifact	Device			Motion	Motion
124	Detect	Detect	Artifact	Object			Motion	Motion
125	Measure	Estimate	Space	Space			Distance	Geometric
126	Move	Propel	Artifact	Device	Material	Liquid		
127	Move	Undulate	Artifact	Object				
128	Change	Control	Artifact	Device			Direction	Motion
129	Change	Regulate	Artifact	Device			Velocity	Motion
130	Detect	Locate	Wave	Sound				

FuncID	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	PropertyType
131	Remove	Extract	Wave	Sound	Wave	Sound		
132	Acquire	Receive	Wave	Sound				
133	Measure	Process	Data	Audio				
134	Detect	Recognize	Living entity	Organism: Human				
135	Measure	Measure	Living entity	Organism: Human				
136	Measure	Process	Living entity	Organism: Human			Measurements	Geometric
137	Measure	Compare	Living entity	Organism: Human	Living entity	Organism: Human		
138	Detect	Detect	Space	Space	Artifact	Object		
139	Detect	Detect	Material	Liquid			Leaking	Motion
140	Stop	Stop	Material	Liquid			Leaking	Motion
141	Move	Move	Material	Solid	Space	Space		
142	Contain	Contain	Material	Liquid				
143	Detect	Detect	Artifact	Object				
144	Measure	Track	Artifact	Object			Position	Motion
145	Increase	Increase	Artifact	Device			Field of view	Geometric
146	Decrease	Reduce	Data	Image				
147	Detect	Recognize	Material	Solid			Pattern	Material
148	Connect	Bind	Material	Solid	Material	Solid		
149	Eject	Discharge	Material	Liquid				
150	Increase	Increase	Material	Liquid			Pressure	Mechanics
151	Increase	Increase	Material	Liquid			Velocity	Motion
152	Provide	Apply	Artifact	Object			Force	Mechanics
153	Move	Lift	Artifact	Object	Living entity	Organism: Human		
154	Detect	Detect	Living entity	Organism: Human			Force	Mechanics
155	Detect	Detect	Living entity	Organism: Human			Angle	Geometric
156	Move	Move	Artifact	Object				
157	Change	Adjust	Artifact	Object			Length	Geometric
158	Provide	Apply	Artifact	Device			Force	Mechanics
159	Detect	Detect	Artifact	Device			Strain	Motion
160	Detect	See	Artifact	Object				
161	Detect	Detect	Material	Solid			Taste	Chemical
162	Detect	Smell	Material	Solid			Odor	Chemical
163	Detect	Hear	Wave	Sound	Artifact	Object		

FuncID	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	PropertyType
164	Detect	Detect	Wave	Sound				
165	Measure	Determine	Wave	Sound			Location	Motion
166	Decrease	Minimize	Artifact	Object			Size	Geometric
167	Detect	Detect	Wave	Sound				
168	Measure	Process	Data	Audio				
169	Detect	Detect	Artifact	Object			Motion	Motion
170	Detect	Detect	Artifact	Object			Trajectory	Motion
171	Detect	Detect	Wave	Sound			Doppler Shift	Waves
172	Detect	Detect	Wave	Sound				
173	Measure	Determine	Wave	Sound			Location	Motion
174	Detect	Detect	Material	Liquid			Motion	Motion
175	Detect	Detect	Material	Solid			Displacement	Motion
176	Change	Convert	Energy	Mechanical	Energy	Electrical		
177	Detect	Detect	Energy	Electromagnetic				
178	Acquire	Absorb	Energy	Thermal				
179	Detect	Detect	Artifact	Object			Expansion	Motion
180	Detect	Detect	Material	Gas			Flow	Motion
181	Detect	Detect	Material	Solid			Deformation	Motion
182	Increase	Amplify	Material	Solid			Strain	Motion
183	Detect	Detect	Material	Solid			Odor	Chemical
184	Detect	Distinguish	Material	Solid	Material	Mixture		
185	Detect	Taste	Material	Liquid				
186	Acquire	Receive	Material	Liquid				
187	Measure	Determine	Material	Solid	Material	Liquid		
188	Detect	Recognize	Material	Solid			Odor	Chemical
189	Detect	Detect	Material	Gas			Concentration	Chemical
190	Collect	Aggregate	Data	Binary	Artifact	Device		
191	Detect	Detect	Wave	Electromagnetic				
192	Measure	Estimate	Living entity	Organism: Animal			Motion	Motion
193	Guide	Navigate	Living entity	Organism: Animal	Material	Gas		
194	Detect	Detect	Artifact	Object			Motion	Motion
195	Detect	Detect	Wave	Electromagnetic				
196	Change	Vary	Artifact	Device			Field of view	Geometric

FuncID	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	PropertyType
197	Change	Control	Artifact	Device			Motion	Motion
198	Detect	Detect	Material	Solid			Motion	Motion
199	Measure	Measure	Material	Solid			Optic flow	Motion
200	Measure	Track	Artifact	Object			Motion	Motion
201	Detect	See	Artifact	Object				
202	Measure	Process	Data	Binary				
203	Detect	Detect	Wave	Electromagnetic			Polarization	Waves
204	Increase	Enhance	Artifact	Object			Visibility	Material
205	Detect	See	Artifact	Object	Material	Liquid		
206	Increase	Enhance	Artifact	Object			Contrast	Material
207	Detect	Detect	Wave	Electromagnetic				
208	Detect	Distinguish	Wave	Electromagnetic			Intensity	Mechanics
209	Detect	Distinguish	Artifact	Object			Color	Material
210	Contain	Store	Data	Binary	Particle	Molecule		
211	Acquire	Absorb	Wave	Electromagnetic				
212	Change	Change	Particle	Molecule			Shape	Geometric
213	Change	Change	Particle	Molecule			Color	Material
214	Contain	Contain	Living entity	Organism: Animal				
215	Stop	Restrict	Living entity	Organism: Human				
216	Contain	Protect	Space	Space				
217	Contain	Store	Data	Binary	Artifact	Object		
218	Provide	Allow	Artifact	Object			Biodegradation	Chemical
219	Increase	Increase	Artifact	Object			Power	Mechanics
220	Provide	Allow	Material	Gas			Motion	Motion
221	Disperse	Distribute	Material	Gas	Artifact	Object		
222	Move	Move	Living entity	Organism: Human	Material	Gas		
223	Create	Generate	Artifact	Object			Lifting force	Mechanics
224	Guide	Direct	Material	Gas			Flow	Motion
225	Change	Control	Living entity	Organism: Human			Motion	Motion
226	Increase	Increase	Artifact	Object			Lifting force	Mechanics
227	Change	Control	Material	Gas			Velocity	Motion
228	Change	Control	Material	Gas			Pressure	Mechanics
229	Communicate	Display	Material	Solid			Color	Material

FuncID	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	PropertyType
230	Increase	Increase	Wave	Electromagnetic			Viewing angle	Geometric
231	Change	Convert	Wave	Electromagnetic	Wave	Electromagnetic		
232	Provide	Allow	Artifact	Object			Bending	Motion
233	Stop	Resist	Artifact	Object			Fracture	Failure
234	Increase	Increase	Artifact	Object			Strength	Material
235	Move	Transmit	Wave	Electromagnetic	Material	Solid		
236	Guide	Redirect	Wave	Electromagnetic				
237	Increase	Increase	Material	Solid			Strength	Material
238	Stop	Resist	Material	Solid			Fracture	Failure
239	Provide	Provide	Material	Solid			Bending stiffness	Material
240	Secure	Support	Living entity	Organism: Human			Weight	Mechanics
241	Move	Transfer	Living entity	Organism: Human			Force	Mechanics
242	Stop	Resist	Artifact	Object			Fracture	Failure
243	Maintain	Hold	Artifact	Object	Material	Solid		
244	Stop	Prevent	Artifact	Object			Motion	Motion
245	Stop	Resist	Artifact	Object			Fracture	Failure
246	Communicate	Display	Material	Solid			Color	Material
247	Create	Cause	Wave	Electromagnetic			Interference	Waves
248	Guide	Redirect	Wave	Electromagnetic				
249	Create	Generate	Artifact	Object			Lifting force	Mechanics
250	Change	Regulate	Artifact	Object			Lifting force	Mechanics
251	Change	Change	Artifact	Object			Shape	Geometric
252	Provide	Allow	Artifact	Object			Bending	Motion
253	Separate	Separate	Material	Solid				
254	Remove	Remove	Material	Solid	Living entity	Organism: Plant		
255	Decrease	Reduce	Artifact	Object			Force	Mechanics
256	Secure	Support	Living entity	Organism: Human			Weight	Mechanics
257	Decrease	Reduce	Living entity	Organism: Human			Force	Mechanics
258	Increase	Increase	Artifact	Object			Friction coefficient	Material
259	Contain	Contain	Artifact	Object				
260	Decrease	Reduce	Artifact	Object			Size	Geometric
261	Increase	Expand	Artifact	Object			Size	Geometric
262	Eject	Deploy	Artifact	Object				

FuncID	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	PropertyType
263	Decrease	Reduce	Artifact	Object			Drag force	Mechanics
264	Decrease	Decrease	Artifact	Object			Friction coefficient	Material
265	Change	Change	Artifact	Object			Shape	Geometric
266	Change	Vary	Artifact	Object			Height	Geometric
267	Provide	Allow	Artifact	Object			Bending	Motion
268	Acquire	Receive	Wave	Sound				
269	Guide	Redirect	Wave	Sound				
270	Detect	Detect	Wave	Sound			Location	Motion
271	Connect	Attach	Material	Solid	Artifact	Object		
272	Connect	Fasten	Artifact	Object	Artifact	Object		
273	Separate	Separate	Material	Solid				
274	Detect	Detect	Material	Solid			Humidity	Thermo-physical
275	Provide	Allow	Artifact	Object			Bending	Motion
276	Move	Open	Artifact	Object				
277	Move	Close	Artifact	Object				
278	Change	Regulate	Space	Space			Temperature	Thermo-physical
279	Change	Regulate	Material	Gas			Motion	Motion
280	Change	Regulate	Material	Gas			Temperature	Thermo-physical
281	Guide	Guide	Material	Gas				
282	Increase	Increase	Artifact	Object			Strength	Material
283	Decrease	Decrease	Artifact	Object			Weight	Mechanics
284	Disperse	Distribute	Artifact	Object			Force	Mechanics
285	Stop	Resist	Artifact	Object			Fracture	Failure
286	Change	Control	Material	Solid			Structure	Material
287	Change	Control	Material	Solid			Size	Geometric
288	Decrease	Reduce	Artifact	Device			Drag force	Mechanics
289	Decrease	Decrease	Artifact	Device			Friction coefficient	Material
290	Provide	Allow	Material	Gas			Motion	Motion
291	Move	Move	Artifact	Device	Material	Liquid		
292	Maintain	Maintain	Artifact	Device			Direction	Motion
293	Move	Move	Artifact	Device	Material	Solid		
294	Rotate	Rotate	Artifact	Device				

Appendix B: Functional Description Template

Appendix B1: Entity Term Definitions

- **Living entity**: An individual form of life (organism) or a biological component (organs, organelles, etc.) that works together to carry on the various processes of life.

    - **Organism:Human**: A member of the genus Homo and especially of the species H. sapiens. A person.

    - **Organism:Animal**: A multicellular organism of the kingdom Animalia, differing from plants in certain typical characteristics such as capacity for locomotion, nonphotosynthetic metabolism, pronounced response to stimuli, restricted growth, and fixed bodily structure.

    - **Organism:Plant**: Any of various photosynthetic, eukaryotic, multicellular organisms of the kingdom Plantae characteristically producing embryos, containing chloroplasts, having cellulose cell walls, and lacking the power of locomotion.

    - **Organism:Fungi**: Any of numerous eukaryotic organisms of the kingdom Fungi, which lack chlorophyll and vascular tissue and range in form from a single cell to a body mass of branched filamentous hyphae that often produce specialized fruiting bodies. The kingdom includes the yeasts, molds, smuts, and mushrooms.

    - **Organism:Protist**: Any of the eukaryotic, unicellular organisms of the kingdom Protista, which includes protozoans, slime molds, and certain algae

    - **Organism:Prokaryote**: A unicellular organism of the kingdom Monera (or Prokaryotae), comprising the bacteria and cyanobacteria, characterized by the absence of a distinct, membrane-bound nucleus or membrane-bound organelles, and by DNA that is not organized into chromosomes.

    - **Organ**: A differentiated part of an organism, such as an eye, wing, or leaf, which performs a specific function.

    - **Tissue**: An aggregation of morphologically similar cells and associated intercellular matter acting together to perform one or more specific functions in the body. There are four basic types of tissue: muscle, nerve, epidermal, and connective.

- **Cell**: The smallest structural unit of an organism that is capable of independent functioning, consisting of one or more nuclei, cytoplasm, and various organelles, all surrounded by a semi-permeable cell membrane.

- **Organelle**: A differentiated structure within a cell, such as a mitochondrion, vacuole, or chloroplast, which performs a specific function.

- **Virus**: Any of a large group of submicroscopic infective agents that are regarded either as extremely simple microorganisms or as extremely complex molecules, that typically contain a protein coat surrounding an RNA or DNA core of genetic material but no semipermeable membrane, that are capable of growth and multiplication only in living cells.

- **Protein**: Any of a group of complex organic macromolecules that contain carbon, hydrogen, oxygen, nitrogen, and usually sulfur and are composed of one or more chains of amino acids. Proteins are fundamental components of all living cells and include many substances, such as enzymes, hormones, and antibodies.

- **Artifact**: A structure not normally present but produced by an external agent or action. An object produced or shaped by human craft, as distinguished from natural objects.

  - **Device**: A functionally related group of interacting, interrelated, or interdependent components forming a complex whole, such as a piece of equipment or a mechanism.

  - **Object**: An individual material thing; a part or component of a device, especially one that can be separated from or attached to the device.

- **Material**: A tangible substance that goes into the makeup of a physical artifact.

  - **Solid**: A substance that does not flow perceptibly under moderate stress, has a definite capacity for resisting forces (as compression or tension) that tend to deform it, and under ordinary conditions retains a definite size and shape. May include composite materials and particulates.

  - **Liquid**: A substance that has no fixed shape but a fixed volume and exhibits a characteristic readiness to flow, little or no tendency to disperse, and relatively high incompressibility.

  - **Gas**: A substance that has neither independent shape nor volume and is characterized by relatively low density and viscosity, relatively great

expansion and contraction with changes in pressure and temperature, the ability to diffuse readily, and the spontaneous tendency to become distributed uniformly throughout any container.

  - **Plasma**: An electrically neutral, highly ionized gas composed of ions, electrons, and neutral particles. A phase of matter distinct from solids, liquids, and normal gases that is often found in stars and fusion reactors.

  - **Mixture**: A composition of two or more substances, in varying proportions, that are not chemically combined with each other and are capable of being separated.

- **Particle**: One of the minute subdivisions of matter. A body having finite mass and internal structure, but negligible dimensions.

  - **Molecule**: The smallest particle of a substance that retains the chemical and physical properties of the substance and is composed of two or more atoms held together by chemical forces.

  - **Atom**: A unit of matter, the smallest unit of an element, having all the characteristics of that element and consisting of a dense, central, positively charged nucleus surrounded by a system of electrons.

  - **Ion**: An atom that has acquired a net electric charge by gaining or losing one or more electrons.

  - **Subatomic particle**: Any of the various units of matter below the size of an atom, including the elementary particles.

- **Wave**: A disturbance traveling through a medium by which energy is transferred from one particle of the medium to another without causing any permanent displacement of the medium itself.

  - **Electromagnetic**: A wave of energy having a frequency within the electromagnetic spectrum that is propagated by simultaneous periodic variations of electric and magnetic field intensity when an electric charge oscillates or accelerates. Includes radio waves, infrared, visible light, ultraviolet, X rays, and gamma rays.

  - **Sound**: A longitudinal pressure wave of audible or inaudible sound.

- **Energy**: The capacity of a physical system to do work. (Note: Energy can also be chosen as a property of an entity).

- **Acoustic energy**: Work performed in the production and transmission of sound.

- **Biological energy**: Work produced by or connected with plants or animals.

- **Chemical energy**: Work resulting from the reactions by which substances are produced from or converted into other substances.

- **Electrical energy**: Work resulting from the flow of electrons from a negative to a positive source.

- **Electromagnetic energy**: Energy that is propagated through free space or through a material medium in the form of electromagnetic waves.

- **Human energy**: Work performed by a person on an entity.

- **Magnetic energy**: Work resulting from materials that have the property of attracting other like materials.

- **Mechanical energy**: Energy associated with the moving parts of a machine or the strain energy associated with a loading state of an object.

- **Nuclear energy**: The energy released by a nuclear reaction, especially by fission or fusion. Also called atomic energy.

- **Thermal energy**: A form of energy that is transferred between bodies as a result of their temperature difference.

- **Space**: An extent or expanse of a surface or three-dimensional area; a blank or empty area.

- **Data**: Numbers, characters, images, or other method of recording, in a form that can be assessed by a human or (especially) input into a computer, stored and processed there, or transmitted on some digital channel.

  - **Binary**: Any file format for digital data encoded as a sequence of bits (binary digits) but not consisting of a sequence of printable characters (text).

  - **Text**: A collection of words, including any alphanumeric characters (letters, numbers, punctuation).

  - **Image**: A visual representation of an object or scene produced on a surface by an optical device or an electronic device. A digital image is

composed of pixels arranged in a rectangular array. Each pixel may consist of one or more bits of information, representing the brightness and color at that point.

- **Audio**: A recording of the audible part of a transmitted signal. Digital audio is a sequence of discrete samples taken from a continuous sound waveform. Digital audio varies in terms of the sampling frequency and the digital encoding (number of bits used).

- **Video**: A recording of moving images that is stored for editing or playback. Digital video is represented by binary numbers (describing color and luminance level) that are readable by computer. Digital video files vary in terms of their image size (pixels) and their frame rate.

Appendix B2: Property Term Definitions

- **Chemical properties**: Any property that describes a chemical or the action of a chemical.
    - **Activation energy**: The minimum energy needed for a specific chemical reaction to occur.
    - **Biodegradation**: The decomposition of organic material by microorganisms.
    - **Chemical energy**: Energy liberated by a chemical reaction or absorbed in the formation of a chemical compound.
    - **Concentration**: The measure of how much of a given substance there is mixed with another substance.
    - **Electro-negativity**: A measure of the attraction that an atom has for the bonding pair of electrons in a covalent bond.
    - **Half-life**: The time required for a substance to decay to half of its initial value.
    - **Odor**: Sensory information of a substance detected through olfaction.
    - **pH**: A measure of the activity of hydrogen ions in a solution and, therefore, its acidity or alkalinity.
    - **Radioactivity**: The spontaneous emission of a stream of particles or electromagnetic rays in nuclear decay.
    - **Reactivity**: The rate at which a chemical substance tends to undergo a chemical reaction in time.
    - **Solubility**: The maximal amount of compound that is soluble in a certain volume of solvent at a specified temperature.
    - **Taste**: Sensory information of a substance detected by the sense of taste."
    - **Toxicity**: A measure of the degree to which something is toxic or poisonous."
- **Electromagnetic properties**: Any property related to the behavior of electric or magnetic fields.

- **Capacitance**: The ability of a capacitor to store potential difference for a given amount of stored charge. Units: Farads.
- **Charge**: A measurement of the charge held by an object. Units: Coulombs.
- **Conductivity**: A measure of how well a material accommodates the transport of electric charge. Units: Siemens per meter.
- **Current**: The amount of flow of charged electrons per unit time. Units: Amperes.
- **Electromagnetic energy**: A form of energy present in any electric field or magnetic field, or in any volume containing electromagnetic radiation. Units: Joules.
- **Inductance**: The characteristic of producing a voltage proportional to the instantaneous rate of change in current flowing through it. Units: Henry.
- **Magnetic flux density**: A measure of the quantity of magnetism per unit area, taking account of the strength and the extent of a magnetic field. Units: Tesla.
- **Potential difference**: The amount of work that a unit charge flowing from the first point to the second can perform. Units: Volts.
- **Resistance**: A measure of the degree to which an electrical component opposes the passage of current. Units: Ohm.

- **Failure properties**: Any property describing the mechanical failure of a material.
  - **Buckling**: The failure to react to the bending moment generated by a compressive load.
  - **Corrosion**: The deterioration of useful properties in a material due to reactions with its environment.
  - **Creep**: The development of additional strains in a material over time.
  - **Fatigue**: The process by which a material is weakened by cyclic loading.
  - **Fracture**: The separation of a body into two, or more, pieces under the action of stress.

    - **Melting**: The process of heating a solid substance to a point where it turns liquid.

    - **Wear**: The erosion of material from a solid surface by the action of another solid.

- **Geometric properties**: Any property that describes a spatial relationship.

    - **Area**: The extent of a planar region or of the surface of a solid measured in square units.

    - **Configuration**: The arrangement of parts or elements of a whole.

    - **Dimension**: A measure of spatial extent, especially width, height, or length.

    - **Perimeter**: The length of a closed curve bounding a plane area.

    - **Quantity**: The measurable, countable, or comparable property or aspect of a thing.

    - **Shape**: The characteristic surface configuration of a thing; an outline or contour.

    - **Volume**: The amount of space occupied by a three-dimensional object or region of space, expressed in cubic units.

- **Material properties**: Any property that describes some aspect or behavior of a material.

    - **Acoustic absorption**: The fraction of incident sound energy absorbed or otherwise not reflected by a surface. Units: % or sabins/ft^2.

    - **Color**: The appearance of objects or light sources described in terms of the individual's perception of them.

    - **Compressibility**: A measure of the relative volume change of a material as a response to a change in pressure or stress.

    - **Density**: The mass per unit volume of a substance under specified conditions of pressure and temperature. Units: kg/m^3.

    - **Emissivity**: A measure of a material's ability to absorb and radiate energy.

    - **Friction coefficient**: A material-dependent value used to calculate the force of friction between two bodies. Measured as the ratio of the

applied force on the body to the normal force on the surface from the body.

- **Hardness**: The characteristic of a solid material expressing its resistance to permanent deformation, as in a scratch or indentation.

- **Material phase**: Any of the forms or states, solid, liquid, gas, or plasma, in which matter can exist, depending on temperature and pressure.

- **Modulus of Elasticity**: Also called Young's modulus, this property is a measure of the elasticity of material and is equal to the uniaxial tensile stress divided by the strain.

- **Modulus of Rigidity**: Also called the shear or torsion modulus, this property is a measure of rigidity and is equal to the shear stress divided by the shear strain.

- **Modulus of Toughness**: A measure of resistance to fracture of a material when suddenly stressed. It is defined as the amount of energy that a material can absorb before breaking.

- **Moment of Inertia**: The resistance of a physical object to angular acceleration, depending upon its shape and the distribution of mass within that shape. Units: kg m^2.

- **Porosity**: The proportion of the non-solid volume (pores and liquid) to the total volume of material.

- **Reflectivity**: The ratio of the energy of a wave reflected from a surface to the energy possessed by the wave striking the surface.

- **Refractive index**: The factor by which electromagnetic radiation is slowed down when it travels inside the material.

- **Reynolds number**: The ratio of inertial forces to viscous forces, used for determining whether a flow will be laminar or turbulent.

- **Surface roughness**: The surface irregularities of a material on a microscopic scale. The average surface roughness is defined as the total area of the peaks and valleys divided by the evaluation length.

- **Ultimate strength**: The maximum applied stress that a material can withstand before failure.

    - **Viscosity**: The degree to which a fluid resists flow under an applied force, measured by the tangential friction force per unit area divided by the velocity gradient under conditions of streamline flow.

    - **Water absorption**: The ratio of the weight of water absorbed by a material, to the weight of the dry materials over a set period of time.

    - **Yield strength**: The applied stress under which an object experiences plastic deformation.

- **Mechanics properties**: Any property related to energy and forces and their effects.

    - **Angular momentum**: A measure of how much the linear momentum is directed around a certain point. The product of the momentum of a rotating body and its distance from the axis of rotation.

    - **Energy**: The capacity of a physical system to do work. Units: J.

    - **Force**: A quantity that tends to produce an acceleration of a body in the direction of its application. Units: N.

    - **Intensity**: A measure of the time-averaged energy flux, or power per unit area. Used most frequently to describe waves (i.e. sound or light). Units: W/m^2.

    - **Mass**: The measure of the quantity of matter that a body or an object contains. Units: kg.

    - **Momentum**: A measure of the motion of a body equal to the product of its mass and velocity.

    - **Power**: The rate at which work is done, expressed as the amount of work per unit time. Alternatively, the rate of change of the energy in a system. Units: W.

    - **Pressure**: Force applied to a unit area of surface. Units: Pa.

    - **Torque**: The moment of a force; the measure of a force's tendency to produce torsion and rotation about an axis.

- **Motion properties**: Any property related to the manner in which a body changes position with respect to time.

    - **Acceleration**: The rate of change of velocity with respect to time. Units: m/s^2.

- **Angular acceleration**: The rate of change of angular velocity with respect to time. Units: rad/s^2.
- **Angular velocity**: The rate of change of angular displacement with respect to time. Units: rad/s.
- **Deformation**: Alteration in the shape or dimensions of an object as a result of the application of stress.
- **Direction**: The relationship by which the alignment or orientation of any position with respect to any other position is established.
- **Location**: A position or point in physical space expressed in relation to other things' positions.
- **Motion**: A change in the position of a body with respect to time
- **Rotation**: The motion of a body around a center or an axis.
- **Translation**: The motion of a body in which every point of the body moves parallel to and the same distance as every other point of the body.
- **Velocity**: A vector measurement of the rate and direction of motion. Units: m/s.
- **Vibration**: A periodic motion of the particles of an elastic body or medium in alternately opposite directions from the position of equilibrium.

- **Thermo-physical properties**: Any property that describes the behavior of heat or its interaction with other bodies.
  - **Boiling point**: The temperature at which a substance changes state from a liquid to a gas.
  - **Enthalpy**: The sum of the internal energy of a system plus the product of its volume multiplied by the pressure exerted on it.
  - **Entropy**: A measure of the amount of energy in a physical system that cannot be used to do work.
  - **Freezing point**: The temperature at which a substance changes state from a liquid to a solid.

- **Melting point**: The temperature at which a substance changes state from a solid to a liquid.

- **Specific heat**: The amount of heat energy required to raise the temperature of one kilogram of a substance by one kelvin.

- **Temperature**: The degree of hotness or coldness of a body or an environment as indicated on or referred to a standard scale.

- **Thermal conductivity**: The quantity of heat transmitted in unit time under steady conditions in a direction normal to a surface of unit area.

- **Thermal energy**: Energy that is transferred between bodies as a result of their temperature difference.

- **Thermal expansion coef**.: A measure of the fractional change in length or volume as temperature increases at constant pressure.

- **Wave properties**: Any property that describes an aspect of a wave, such as a sound wave or electromagnetic wave.

  - **Amplitude**: The magnitude of the maximum disturbance in the medium during one wave cycle.

  - **Attenuation**: The decrease in intensity of a wave as a result of absorption of energy and of scattering out of the path.

  - **Frequency**: The number of cycles of a repetitive waveform per second. Units: Hz.

  - **Phase**: The position of a feature of a wave, typically a peak or a trough of the waveform, to that same feature in another part of the waveform, or on a second waveform.

  - **Wavelength**: The distance between analogous points on any two successive waves.

Appendix B3: Action Term Definitions

- **Create**: To cause to exist
- **Copy**: To make a reproduction
- **Destroy**: To ruin completely
- **Provide**: To make available
- **Acquire**: To gain possession of
- **Remove**: To take away
- **Inject**: To force or drive into
- **Eject**: To throw out forcefully
- **Move**: To change the place or position of
- **Rotate**: To turn around on an axis or center
- **Position**: To put in place or position
- **Guide**: To direct the course of
- **Collect**: To bring together in a group
- **Disperse**: To drive off or scatter in different directions
- **Connect**: To join or fasten together
- **Mix**: To combine or blend into one
- **Separate**: To set or keep apart
- **Contain**: To hold or keep within limits
- **Secure**: To make firm or tight
- **Change**: To cause to be different
- **Maintain**: To keep in an existing state
- **Start**: To set into motion, operation, or activity

- **Stop**: To halt the motion or progress of
- **Increase**: To make greater or larger
- **Decrease**: To grow less or smaller
- **Detect**: To discover or ascertain the existence, presence, or fact of
- **Measure**: To ascertain the dimensions, quantity, or capacity of
- **Communicate**: To convey information about
- **Record**: To set down for preservation in writing or other permanent form
- **Specify**: To state explicitly or in detail

Appendix B4: Action Term Synonyms

- **Create**: Assemble, Bear, Beget, Breed, Brew, Bring About, Bring Forth, Build, Cast, Cause, Compose, Concoct, Construct, Contrive, Craft, Design, Develop, Devise, Engineer, Erect, Establish, Evolve, Fabricate, Fashion, Forge, Form, Formulate, Generate, Invent, Machine, Make, Manufacture, Mold, Originate, Produce, Set Up, Shape, Spawn, Synthesize, Yield

- **Copy**: Clone, Double, Duplicate, Emulate, Imitate, Mime, Mimic, Mirror, Model, Photocopy, Recreate, Replicate, Reproduce, Simulate, Xerox

- **Destroy**: Annihilate, Break, Break apart, Break down, Break up, Conquer, Crush, Damage, Decimate, Delete, Demolish, Destruct, Disassemble, Dismantle, Eliminate, Eradicate, Erase, Exterminate, Extinguish, Kill, Obliterate, Ruin, Smash, Spoil, Take apart, Take down, Tear down, Undo, Unmake, Wipe out, Wreck

- **Provide**: Accommodate, Administer, Allow, Apply, Bring forward, Contribute, Deliver, Deposit, Dispense, Distribute, Feed, Give, Grant, Introduce, Offer, Output, Present, Produce, Return, Serve, Submit, Supply, Yield

- **Acquire**: Absorb, Accept, Accrue, Adopt, Assimilate, Bring In, Capture, Carry in, Catch, Collect, Consume, Gain, Gather Up, Get, Grab, Import, Imbibe, Ingest, Obtain, Pick Up, Procure, Pull In, Receive, Recover, Recruit, Retrieve, Seize, Take, Take In, Trap

- **Remove**: Abduct, Carry away, Carry off, Cart away, Cart off, Cast aside, Cast off, Clear, Clear away, Clear off, Cut off, Cut out, Delete, Discard, Displace, Draw, Drop, Dump, Empty, Erase, Evacuate, Export, Expunge, Extract, Haul away, Haul off, Pull out, Subtract, Take away, Take out, Throw away, Toss away, Toss out, Trash, Wash away, Wash out, Wear away, Withdraw

- **Inject**: Add, Administer, Dispense, Drive in, Embed, Force in, Give, Implant, Infuse, Input, Insert, Introduce, Plug in, Put in, Shoot in

- **Eject**: Cast out, Deploy, Deport, Discharge, Dispatch, Drive out, Emit, Evict, Expel, Extrude, Force out, Kick out, Launch, Output, Propel, Release, Secrete, Spit out, Throw out

- **Move**: Advance, Bring, Channel, Circulate, Close, Conduct, Deliver, Displace, Download, Drag, Drive, Force, Forward, Launch, Lift, Locomote, Open, Oscillate, Pass, Progress, Project, Propagate, Propel, Pull, Push, Relay, Relocate, Send, Shift, Shoot, Slide, Tow, Transfer, Translate, Translocate, Transmit, Transplant, Transport, Undulate, Upload, Vibrate

- **Rotate**: Circle, Circumvolve, Flip, Go around, Gyrate, Orbit, Pivot, Revolve, Roll, Spin, Spiral, Swivel, Turn, Twist, Yaw

- **Position**: Align, Arrange, Center, Level, Locate, Order, Perch, Place, Plant, Poise, Pose, Put, Seat, Set, Sit, Situate, Square, Stand, Station

- **Guide**: Aim, Align, Channel, Conduct, Control, Direct, Focus, Govern, Lead, Line up, Maneuver, Navigate, Operate, Orient, Pilot, Point, Redirect, Steer, Target

- **Collect**: Accumulate, Aggregate, Amass, Assemble, Cluster, Collocate, Compile, Gather, Group, Lump, Pile up, Pull together, Round up

- **Disperse**: Deploy, Diffuse, Disband, Dispel, Disseminate, Dissipate, Dissolve, Distribute, Scatter, Spray, Spread, Spread out

- **Connect**: Add, Adhere, Affix, Append, Attach, Bind, Bond, Bring together, Conjoin, Couple, Fasten, Fix, Glue, Join, Link, Mate, Partner, Put together, Splice, Tape, Tether, Tie, Unite, Weld

- **Mix**: Admix, Amalgamate, Blend, Coalesce, Combine, Commingle, Commix, Compound, Conflate, Fuse, Immingle, Immix, Integrate, Intermingle, Intermix, Join, Merge, Mingle, Stir, Unify, Unite

- **Separate**: Bisect, Branch, Break, Break off, Break up, Cut, Cut off, Decouple, Detach, Disconnect, Disjoin, Dislocate, Dissect, Dissever, Disunite, Divide, Draw apart, Fracture, Fragment, Intersect, Isolate, Part, Partition, Polarize, Seclude, Section, Segment, Set apart, Sever, Slice, Split, Split up, Take apart, Tear, Unbind, Uncouple, Unhook, Unlink

- **Contain**: Border, Bound, Box in, Cache, Confine, Cover, Embrace, Encircle, Enclose, Encompass, Frame, Guard, Hold, Include, Incorporate, Keep, Pack, Put away, Protect, Reserve, Retain, Save, Store, Surround

- **Secure**: Affix, Anchor, Brace, Clamp, Fasten, Fix, Fortify, Ground, Hitch, Hold, Lock, Pin down, Reinforce, Root, Seal, Set, Stabilize, Steady, Support, Suspend, Tether

- **Change**: Adapt, Adjust, Alter, Alternate, Amend, Attune, Calibrate, Condition, Control, Convert, Edit, Evolve, Exchange, Flip, Interchange, Invert, Manipulate, Metamorphose, Modify, Modulate, Morph, Mutate, Phase, Regulate, Replace, Reverse, Shape, Shift, Skew, Substitute, Swap, Switch, Toggle, Trade, Transform, Transmute, Turn, Vary

- **Maintain**: Balance, Conserve, Continue, Control, Have, Hold, Keep, Keep up, Manage, Perpetuate, Preserve, Regulate, Resume, Retain, Sustain, Stabilize, Steady, Uphold

- **Start**: Activate, Actuate, Animate, Begin, Carry out, Cause, Commence, Enable, Execute, Incite, Induce, Initiate, Launch, Load, Motivate, Operate, Originate, Play, Power, Prompt, Provoke, Set off, Spark, Trigger, Turn on, Use

- **Stop**: Abort, Arrest, Avert, Avoid, Barricade, Block, Blockade, Bound, Cancel, Cease, Close, Complete, Conclude, Constrain, Counteract, Culminate, Curb, Defend, Delay, Deflect, Desist, Disable, Discontinue, Disrupt, Disturb, End, Expire, Finish, Forbid, Halt, Hinder, Hold, Hold back, Immobilize, Impede, Inhibit, Intercept, Intermit, Interrupt, Jam, Limit, Moderate, Obstruct, Occlude, Oppose, Pause, Prevent, Prohibit, Protect, Quit, Resist, Restrain, Restrict, Retire, Shut off, Stall, Subdue, Suppress, Suspend, Terminate, Turn off

- **Increase**: Accrete, Add, Amplify, Augment, Boost, Broaden, Develop, Double, Enhance, Enlarge, Expand, Extend, Grow, Increment, Intensify, Magnify, Maximize, Multiply, Raise, Step up

- **Decrease**: Attenuate, Condense, Contract, Cut down, Decay, Decrement, Diminish, Drop, Fade, Lessen, Lower, Minimize, Reduce, Shrink

- **Detect**: Ascertain, Discover, Distinguish, Expose, Feel, Find, Hear, Identify, Listen to, Locate, Notice, Observe, Perceive, Read, Receive, Recognize, See, Sense, Sight, Smell, Spot, Taste, Trace, Uncover

- **Measure**: Assess, Calculate, Check, Clock, Compare, Compute, Count, Determine, Estimate, Evaluate, Examine, Figure, Gauge, Grade, Judge, Order, Process, Quantify, Rank, Rate, Review, Scale, Score, Size, Test, Time, Track, Weigh

- **Communicate**: Advise, Alarm, Alert, Announce, Apprise, Call, Caution, Command, Convey, Declare, Depict, Describe, Detail, Display, Educate, Explain, Expose, Express, Gesture, Identify, Illustrate, Impart, Indicate, Inform, Instruct, List, Message, Name, Notify, Order, Portray, Post, Present, Project, Relate, Relay, Render, Report, Represent, Reveal, Say, Show, Signal, Sound, Speak, State, Symbolize, Teach, Tell, Verbalize, Visualize, Warn

- **Record**: Catalogue, Chart, Chronicle, Cite, Copy, Diagram, Document, Draw, Enter, File, Graph, Hold, Index, Inscribe, Keep, List, Log, Mark, Note, Plot, Post, Print, Put down, Register, Report, Save, Score, Store, Tag, Tally, Tape, Write,

- **Specify**: Assign, Choose, Cite, Decide, Declare, Define, Delineate, Describe, Designate, Detail, Determine, Elect, Establish, Explain, Indicate, Fix, Name, Pick, Plan, Propose, Quantify, Select, Set, State, Stipulate

Appendix B5: Application Instructions

Getting Started

This form uses the Functional Template method to record your functional statements. To record the functional statements from a functional decomposition of a product, there are the following steps:

1. Define use environment
   1a. Identify entities
   1b. Identify properties
2. Record functions

In this method, you first explicitly define the use-environment of a product. The use environment is defined as the set of entities and their properties with which the product interacts in its lifetime to carry out its intended functions. The entities in the use environment are the objects, whether they are physical or non-physical, on which the functions of the product will be acting. The use environment consists of two types of entities. The first type describes entities that are external to the device and are present regardless of the design of the product. Such entities are commonly inputs or outputs of the system. The second type describes entities that are internal to the device, such as components, or even the product itself. The relevant properties of these entities are also identified as part of the use environment. The entities and properties of the use environment are explicitly identified because they are referred to in the functional statements of the product that will later be recorded.

Example

Consider a steam iron. The external entities for a steam iron would include the following: user, clothing, water, steam, heat, and power source. The relevant properties of these entities would include the wrinkles in the clothing and the pressure on the clothing. The internal entities would include the iron and the base and such relevant properties as the temperature of the base.

Step 1a: Identify entities

In this step, identify all the entities in your use-environment. To add an entity, the following steps are employed.

1. In the box next to "Entity name", type in the name of the entity that you wish to add.

2. Using the lists in the two columns next to "Entity type", specify the type of entity that you are adding. This information will be archived for future searches. In the first column, select the category that best describes your entity. Then, in the second column, select a more specific entity type from your chosen category. Definitions of the selected term are provided in the yellow box below the list labeled "Entity Description."

3. Add the entity by clicking the "Add entity" button. Once added, the entity name and type will appear in the "Entity Summary" list on the right side of the screen. If you wish to remove an entity from the list, you may do so by selecting the added entity and then clicking the "Remove entity" button.

Example

In the case of the steam iron, to enter the entity “base”, first type in “base” or an expanded version “base of the iron”. Next, select the category “Artifact”, which describes a man-made object, and then select “Object” which describes a component of a device. This entity can then be added by clicking the “Add entity” button and then you can repeat the steps for your remaining entities.

Step 1b: Identify properties of entities

In this step, identify any properties of the entities that were added in the previous step that are of importance in the use of the product. To add a property, follow the steps below.

1. In the menu next to "Select entity", select the entity to which you would like to add a property. All of the previously identified entities will appear in this menu.

2. Using the lists in the two columns next to "Property", select the property that you wish to add. In the first list, select the type of property to be added. Then, in the second list, select a property. If "*Other" is chosen from the end of the list, type in the property in the text box that appears below the list. Definitions of the selected term are provided in the yellow box below the list labeled "Property Description".

3. Add the property by clicking the "Add property" button. Once added, the property and the entity to which it belongs will appear in the "Property Summary" list on the right side of the screen. If you wish to remove a property from the list, you may do so by selecting the added property and then clicking the "Remove property" button.

Example

In the case of the steam iron, to enter the property “temperature of base” for example, the user would select “base” from the menu of added entities. Next, “Thermo-physical” would be selected as the type of property, and then “temperature” would be selected as the property. If this term were not available, the user would select “*Other” and then proceed to type in “temperature”. Once the property is selected or typed in, it can be added by clicking the "Add property" button, and then these steps can be repeated for the remaining properties.

Step 2: Record Functions

In this step, you will form the functional statements using the entities and properties that were previously identified. In order to record each of these functional statements at each level in your functional decomposition hierarchy, the following steps are employed.

1. Using the menus in the two columns next to "Select action", select the action term that most accurately represents your functional statement. The first menu provides 30 action terms from which to choose, and the second menu provides a list of synonyms for each these terms. Definitions of the 30 action terms are provided in the yellow box below the menus labeled "Action Definition".

2. Using the menu next to "Select Usage", select the sentence structure of the functional statement that you will subsequently record. The first option is for simple verb-noun functions, such as “store water”. The second option is for functions that use more than one entity, such as “allow water into iron”. The last option is for functions that use a property, such as “adjust base temperature”.

3. On the right side of the screen, the functional statement is now formed. The selected action term will already be present and drop-down menus are used to select the desired entities or properties. If required, a text box will be provided to enter prepositions. If the desired entity or property does not appear in the menus, you may return to Step 1 to add it.

4. To add the functional statement to the “Function Summary”, enter the “Function ID” number that appears in your functional decomposition next to your corresponding function and then click the "Add Function" button. If you wish to remove a functional statement from the list, you may do so by selecting the function and then clicking the "Remove function" button.

Repeat steps 1-4 for each of the remaining functional statements in your decomposition. After you have added all of your functional statements, submit them by entering your “User ID” number and then clicking the "Submit Functions" button.

Example

In the case of the steam iron, to enter the functional statement “adjust base temperature”, first the action term “change” is selected since it has the closest in meaning to the term “adjust”. The synonym “adjust” is then selected from the second menu. Next, the third usage is selected to record a functional statement that describes a property. The correct template will now appear on the right side of the screen with the action term “adjust” already present. The property “temperature” is selected from the provided menu, causing the associated entity “base” to appear in the functional statement. Then, the preposition “of” is typed into the provided text box. The functional statement “adjust temperature of base” can now be added by entering the unique Function ID number from the functional decomposition and then clicking the "Add Function" button.

Appendix C: Functional Basis

Appendix C1: Function Term Definitions

- **Branch**: To cause a flow (material, energy, signal) to no longer be joined or mixed.
    - **Separate**: To isolate a flow (material, energy, signal) into distinct components. The separated components are distinct from the original flow, as well as each other. Example: glass prism *separates* light into different wavelength components to produce a rainbow.
        - **Divide**: To split up a flow into parts or to classify distinct parts of a flow. Example: A vending machine divides the solid form of coins into appropriate denominations.
        - **Extract**: To draw, or forcibly pull out, a flow. Example: A vacuum cleaner *extracts* debris from the imported mixture and exports clean air to the environment.
        - **Remove**: To take away a part of a flow from its prefixed place. Example: A sander *removes* small pieces of the wood surface to smooth the wood.
    - **Distribute**: To cause a flow (material, energy, signal) to break up. The individual bits are similar to each other and the undistributed flow. Example: An atomizer *distributes* (or sprays) hair-styling liquids over the head to hold the hair in the desired style.
- **Channel**: To cause a flow (material, energy, signal) to move from one location to another location.
    - **Import**: To bring in a flow (material, energy, signal) from outside the system boundary. Example: A physical opening at the top of a blender pitcher *imports* a solid (food) into the system. Also, a handle on the blender pitcher imports a human hand.
    - **Export**: To send a flow (material, energy, signal) outside the system boundary. Example: Pouring blended food out of a standard blender pitcher *exports* liquid from the system. The opening at the top of the blender is a solution to the export sub-function.
    - **Transfer**: To shift, or convey, a flow (material, energy, signal) from one place to another.

        - **Transport**: To move a material from one place to another. Example: A coffee maker *transports* liquid (water) from its reservoir through its heating chamber and then to the filter basket.

        - **Transmit**: To move an energy from one place to another. Example: In a hand held power sander, the housing of the sander *transmits* human force to the object being sanded.

    - **Guide**: To direct the course of a flow (material, energy, signal) along a specific path. Example: A domestic HVAC system *guides* gas (air) around the house to the correct locations via a set of ducts.

        - **Translate**: To fix the movement of a flow by a device into one linear direction. Example: In an assembly line, a conveyor belt *translates* partially completed products from one assembly station to another.

        - **Rotate**: To fix the movement of a flow by a device around one axis. Example: A computer disk drive *rotates* the magnetic disks around an axis so that the head can read data.

        - **Allow degree of freedom (DOF)**: To control the movement of a flow by a force external to the device into one or more directions. Example: To provide easy trunk access and close appropriately, trunk lids need to move along a specific degree of freedom. A four bar linkage *allows a rotational DOF* for the trunk lid.

- **Connect**: To bring two or more flows (material, energy, signal) together.

    - **Couple**: To join or bring together flows (material, energy, signal) such that the members are still distinguishable from each other. Example: A standard pencil couples an eraser and a writing shaft. The coupling is performed using a metal sleeve that is crimped to the eraser and the shaft.

        - **Join**: To couple flows together in a predetermined manner. Example: A ratchet *joins* a socket on its square shaft interface.

        - **Link**: To couple flows together by means of an intermediary flow. Example: A turnbuckle *links* two ends of a steering cable together.

- **Mix**: To combine two flows (material, energy, signal) into a single, uniform homogeneous mass. Example: A shaker *mixes* a paint base and its dyes to form a homogeneous liquid.

- **Control Magnitude**: To alter or govern the size or amplitude of a flow (material, energy, signal).

  - **Actuate**: To commence the flow of energy, signal, or material in response to an imported control signal. Example: A circuit switch *actuates* the flow of electrical energy and turns on a light bulb.

  - **Regulate**: To adjust the flow of energy, signal, or material in response to a control signal, such as a characteristic of a flow. Example: Turning the valves *regulates* the flow rate of the liquid flowing from a faucet.

    - **Increase**: To enlarge a flow in response to a control signal. Example: Opening the valve of a faucet further *increases* the flow of water.

    - **Decrease**: To reduce a flow in response to a control signal. Example: Closing the value further *decreases* the flow of propane to the gas grill.

  - **Change**: To adjust the flow of energy, signal, or material in a predetermined and fixed manner. Example: In a hand held drill, a variable resistor *changes* the electrical energy flow to the motor thus changing the speed the drill turns.

    - **Increment**: To enlarge a flow in a predetermined and fixed manner. Example: A magnifying glass *increments* the visual signal (i.e. the print) from a paper document.

    - **Decrement**: To reduce a flow in a predetermined and fixed manner. Example: The gear train of a power screwdriver *decrements* the flow of rotational energy.

    - **Shape**: To mold or form a flow. Example: In the auto industry, large presses *shape* sheet metal into contoured surfaces that become fenders, hoods and trunks.

    - **Condition**: To render a flow appropriate for the desired use. Example: To prevent damage to electrical equipment, a surge protector *conditions* electrical energy by excluding spikes and noise (usually through capacitors) from the energy path.

- **Stop**: To cease, or prevent, the transfer of a flow (material, energy, signal). Example: A reflective coating on a window *stops* the transmission of UV radiation through a window.

    - **Prevent**: To keep a flow from happening. Example: A submerged gate on a dam wall *prevents* water from flowing to the other side.

    - **Inhibit**: To significantly restrain a flow, though a portion of the flow continues to be transferred. Example: The structures of space vehicles *inhibits* the flow of radiation to protect crew and cargo.

- **Convert**: To change from one form of a flow (material, energy, signal) to another. For completeness, any type of flow conversion is valid. In practice, conversions such as convert electricity to torque will be more common than convert solid to optical energy. Example: An electrical motor *converts* electricity to rotational energy.

- **Provision**: To accumulate or provide a material or energy flow.

    - **Store**: To accumulate a flow. Example: A DC electrical battery *stores* the energy in a flashlight.

        - **Contain**: To keep a flow within limits. Example: A vacuum bag *contains* debris vacuumed from a house.

        - **Collect**: To bring a flow together into one place. Example: Solar panels *collect* ultra-violet sun rays to power small mechanisms.

    - **Supply**: To provide a flow from storage. Example: In a flashlight, the battery *supplies* energy to the bulb.

- **Signal**: To provide information on a material, energy or signal flow as an output signal flow. The information providing flow passes through the function unchanged.

    - **Sense**: To perceive, or become aware, of a flow. Example: An audiocassette machine *senses* if the end of the tape has been reached.

        - **Detect**: To discover information about a flow. Example: A gauge on the top of a gas cylinder *detects* proper pressure ranges.

        - **Measure**: To determine the magnitude of a flow. Example: An analog thermostat *measures* temperature through a bimetallic strip.

- **Indicate**: To make something known to the user about a flow. Example: A small window in the water container of a coffee maker *indicates* the level of water in the machine.
    - **Track**: To observe and record data from a flow. Example: By *tracking* the performance of batteries, the low efficiency point can be determined.
    - **Display**: To reveal something about a flow to the mind or eye. Example: The xyz-coordinate display on a vertical milling machine *displays* the precise location of the cutting tool.
- **Process**: To submit information to a particular treatment or method having a set number of operations or steps. Example: A computer *processes* a login request signal before allowing a user access to its facilities.

- **Support**: To firmly fix a material into a defined location, or secure an energy or signal into a specific course.
    - **Stabilize**: To prevent a flow from changing course or location. Example: On a typical canister vacuum, the center of gravity is placed at a low elevation to *stabilize* the vacuum when it is pulled by the hose.
    - **Secure**: To firmly fix a flow path. Example: On a bicycling glove, a Velcro strap *secures* the human hand in the correct place.
    - **Position**: To place a flow (material, energy, signal) into a specific location or orientation. Example: The coin slot on a soda machine *positions* the coin to begin the coin evaluation and transportation procedure.

Appendix C2: Flow Term Definitions

- **Material**
    - **Human**: All or part of a person who crosses the device boundary. Example: Most coffee makers require the flow of a *human hand* to actuate (or start) the electricity and thus heat the water.
    - **Gas**: Any collection of molecules characterized by random motion and the absence of bonds between the molecules. Example: An oscillating fan moves air by rotating blades. The air is transformed as *gas* flow.
    - **Liquid**: A readily flowing fluid, specifically having its molecules moving freely with respect to each other, but because of cohesive forces, not expanding indefinitely. Example: The flow of water through a coffee maker is a *liquid*.
    - **Solid**: Any object with mass having a definite, firm shape. Example: The flow of sandpaper into a hand sander is transformed into a *solid* entering the sander.
        - **Object**: Material that can be seen or touched that occupies space. Example: The box of scrap paper for recycling is represented as the flow *object*.
        - **Particulate**: Substance containing minute separate particles. Example: Granular sugar and powdered paint are *particulates*.
        - **Composite**: Solid material composed of two or more substances having different physical characteristics and in which each substance retains its identity while contributing desirable properties to the whole unit. Any class of high-strength, lightweight engineering materials consisting of various combinations of alloys, plastics, and ceramics. Example: Materials such as wood, fiberglass combined with metals, ceramics, glasses, or polymers together are considered a *composite*. Kevlar cloth combined with paper honeycomb by means of a resin is considered a *composite*.
    - **Plasma:** A collection of charged particles that is electrically neutral exhibiting some properties of a gas, but differing from a gas in being a good conductor of electricity and in being affected by a magnetic field. Example: Plasma cutting focuses an intense beam of ionized air, known as *plasma*, produced by an electric arc, which melts the material to be cut.

- **Mixture**: A substance containing two or more components which are not in fixed proportions, do not lose their individual characteristics and can be separated by physical means. Example: Expected precipitation for this evening is a *mixture* of rain, sleet, and snow.

    - **Liquid-liquid**: A readily flowing combination of two or more fluids, specifically having its molecules moving freely with respect to each other, but because of cohesive forces, not expanding indefinitely. Example: Machine oil and gasoline is a common *liquid-liquid* mixture used in yard maintenance machines.

    - **Gas-gas**: A collection of molecules containing two or more components, which are characterized by random motion and the absence of bonds between the molecules. Example: The mixture of argon and carbon dioxide, a *gas-gas* flow, is commonly used in welding.

    - **Solid-solid**: A combination of two or more objects with mass having definite, firm shape. Example: Pebbles, sand, gravel, and slag can be used to form concrete, mortar, or plaster. After it cures, concrete is a *solid-solid*.

    - **Solid-Liquid**: A combination of two or more components containing at least one solid and one liquid. Example: Iced Tea is a *solid-liquid* mixture of ice (solid), water (liquid), and tea grounds (solid).

    - **Solid-Gas**: A combination of two or more components containing at least one solid and one gas. Example: Fog is a *solid-gas* mixture of frozen ice particles (solid) in air (gas).

    - **Liquid-Gas**: A combination of two or more components containing at least one liquid and one gas. Example: Carbonated drinks are *liquid-gas* mixtures of flavored syrup (liquid), purified water (liquid), and carbon dioxide (gas).

    - **Solid-Liquid-Gas**: A combination or three or more components containing at least one each of a solid, liquid, and gas. Example: In a cup of soda and ice cubes, the cup contains the *solid-liquid-gas* flow.

    - **Colloidal**: A solid, liquid, or gaseous substance made up of very small, insoluble non-diffusible particles that remain in suspension in a surrounding solid, liquid, or gaseous medium of a different matter. Example: Aerosols, smoke, and mist can

all be considered *colloids*. Mist is a combination of very fine water droplets suspended in air.

- **Energy**
    - **Generic Complements**.
        - **Effort**: Any component of energy used to accomplish an intended purpose.
        - **Flow**: Any component of energy causing the intended object to move or run freely.
    - **Human**: Work performed by a person on a device. Example: An automobile requires the flow of *human energy* to steer and accelerate the vehicle.
        - **Force**: Human effort that is input to the system without regard for the required motion. Example: *Human force* is needed to actuate the trigger of a toy gun.
        - **Velocity**: Activity requiring movement of all or part of the body through a prescribed path. Example: The track pad on a laptop computer receives the flow of *human velocity* to control the cursor.
    - **Acoustic**: Work performed in the production and transmission of sound. Example: The motor of a power drill generates the flow of *acoustic energy* in addition to the torque.
        - **Pressure**: The pressure field of the sound waves. Example: A condenser microphone has a diaphragm, which vibrates in response to *acoustic pressure*. This vibration changes the capacitance of the diaphragm, thus superimposing an alternating voltage on the direct voltage applied to the circuit.
        - **Particle velocity**: The speed at which sound waves travel through a conducting medium. Example: Sonar devices rely on the flow of *acoustic particle velocity* to determine the range of an object.
    - **Biological**: Work produced by or connected with plants or animals. Example: In poultry houses, grain is fed to chickens, which is then converted into *biological energy*.

        - **Pressure**: The pressure field exerted by a compressed biological fluid. Example: The high concentration of sugars and salts inside a cell causes the entry, via osmosis, of water into the vacuole, which in turn expands the vacuole and generates a hydrostatic *biological pressure*, called turgor, that presses the cell membrane against the cell wall. Turgor is the cause of rigidity in living plant tissue.

        - **Volumetric flow**: The kinetic energy of molecules in a biological fluid flow. Example: Increased metabolic activity of tissues such as muscles or the intestine automatically induces increased *volumetric flow* of blood through the dilated vessels.

    - **Chemical**: Work resulting from the reactions by which substances are produced from or converted into other substances. Example: A battery converts the flow of *chemical energy* into electrical energy.

        - **Affinity**: The force with which atoms are held together in chemical bonds. Affinity is proportional to the chemical potential of a compounds constituent species. Example: An internal combustion engine transforms the chemical *affinity* of the gas into a mechanical force.

        - **Reaction rate**: The speed or velocity at which chemical reactants produce products. Reaction rate is proportional to the mole rate of the constituent species. Example: Special coatings on automobile panels stop the *chemical reaction rate* of the metal with the environment.

    - **Electrical**: Work resulting from the flow of electrons from a negative to a positive source. Example: A power belt sander imports a flow of *electrical energy* (electricity, for convenience) from a wall outlet and transforms it into a rotation.

        - **Electromotive force**: Potential difference across the positive and negative sources. Example: Household electrical receptacles provide a flow of *electromotive force* of approximately 110 V.

        - **Current**: The flow or rate of flow of electric charge in a conductor or medium between two points having a difference in potential. Example: Circuit breakers trip when the *current* exceeds a specified limit.

    - **Electromagnetic**: Energy that is propagated through free space or through a material medium in the form of electromagnetic waves (Britannica

Online, 1997). It has both wave and particle-like properties. Example: Solar panels convert the flow *electromagnetic energy* into electricity.

- **Generic Complements**.
  - **Effort**: Any component of electromagnetic energy used to accomplish an intended purpose.
  - **Flow**: Any component of electromagnetic energy causing the intended object to move or run freely.

- **Optical**: Work associated with the nature and properties of light and vision. Also, a special case of solar energy (see solar). Example: A car visor refines the flow of *optical energy* that its passengers receive.
  - **Intensity**: The amount of optical energy per unit area. Example: Tinted windows reduce the *optical intensity* of the entering light.
  - **Velocity**: The speed of light in its conducting medium. Example: NASA developed and tested a trajectory control sensor (TCS) for the space shuttle to calculate the distance between the payload bay and a satellite. It relied on the constancy of the *optical velocity* flow to calculate distance from time of flight measurements of a reflected laser.

- **Solar**: Work produced by or coming from the sun. Example: Solar panels collect the flow of *solar energy* and transform it into electricity.
  - **Intensity**: The amount of solar energy per unit area. Example: A cloudy day reduces the *solar intensity* available to solar panels for conversion to electricity.
  - **Velocity**: The speed of light in free space. Example: Unlike most energy flows, *solar velocity* is a well-known constant.

- **Hydraulic**: Work that results from the movement and force of a liquid, including hydrostatic forces. Example: Hydroelectric dams generate electricity by harnessing the *hydraulic energy* in the water that passes through the turbines.

- **Pressure**: The pressure field exerted by a compressed liquid. Example: A hydraulic jack uses the flow *hydraulic pressure* to lift heavy objects.

- **Volumetric flow**: The movement of fluid molecules. Example: A water meter measures the *volumetric flow* of water without a significant pressure drop in the line.

- **Magnetic**: Work resulting from materials that have the property of attracting other like materials, whether that quality is naturally occurring or electrically induced. Example: The *magnetic energy* of a magnetic lock is the flow that keeps it secured to the iron based structure.

  - **Magnetomotive force**: The driving force which sets up the magnetic flux inside of a core. Magnetomotive force is directly proportional to the current in the coil surrounding the core. Example: In a magnetic door lock, a change in *Magnetomotive force* (brought about by a change in electrical current) allows the lock to disengage and the door to open.

  - **Magnetic flux rate**: Flux is the magnetic displacement variable in a core induced by the flow of current through a coil. The magnetic flow variable is the time rate of change of the flux. The voltage across a magnetic coil is directly proportional to the time rate of change of magnetic flux. Example: A magnetic relay is a transducer that senses the time rate of change of *magnetic flux* when the relay arm moves.

- **Mechanical**: Energy associated with the moving parts of a machine or the strain energy associated with a loading state of an object. Example: An elevator converts electrical or hydraulic energy into mechanical energy.

  - **Generic Complements**.

    - **Effort**: Any component of mechanical energy used to accomplish an intended purpose.

    - **Flow**: Any component of mechanical energy causing the intended object to move or run freely.

  - **Rotational energy**: Energy that results from a rotation or a virtual rotation. Example: Customers are primarily concerned with the flow of *rotational energy* from a power screwdriver.

        - **Torque**: Pertaining to the moment that produces or tends to produce rotation. Example: In a power screwdriver, electricity is converted into rotational energy. The more specific flow is *torque*, based on the primary customer need to insert screws easily, not quickly.

        - **Angular velocity**: Pertaining to the orientation or the magnitude of the time rate of change of angular position about a specified axis. Example: A centrifuge is used to separate out liquids of different densities from a mixture. The primary flow it produces is that of *angular velocity*, since the rate of rotation about an axis is the main concern.

    - **Translational energy**: Energy flow generated or required by a translation or a virtual translation. Example: A child's toy, such as a projectile launcher, transmits *translational energy* to the projectile to propel it away.

        - **Force**: The action that produces or attempts to produce a translation. Example: In a tensile testing machine, the primary flow of interest is that of a *force* which produces a stress in the test specimen.

        - **Linear velocity**: Motion that can be described by three component directions. Example: An elevator car uses the flow of *linear velocity* to move between floors.

- **Pneumatic**: Work resulting from a compressed gas flow or pressure source. Example: A BB gun relies on the flow of *pneumatic energy* (from compressed air) to propel the projectile (BB).

    - **Pressure**: The pressure field exerted by a compressed gas. Example: Certain cylinders rely on the flow of *pneumatic pressure* to move a piston or support a force.

    - **Mass flow**: The kinetic energy of molecules in a gas flow. Example: The *mass flow* of air is the flow that transmits the thermal energy of a hair dryer to damp hair.

- **Radioactive (Nuclear)**: Work resulting from or produced by particles or rays, such as alpha, beta and gamma rays, by the spontaneous disintegration of atomic nuclei. Example: Nuclear reactors produce a flow of *radioactive energy* which heats water into steam and then drives electricity generating turbines.

        - **Intensity**: The amount of radioactive particles per unit area. Example: Concrete is an effective radioactive shielding material, reducing the *radioactive intensity* in proportion to its thickness.

        - **Decay rat**e: The rate of emission of radioactive particles from a substance. Example: The *decay rate* of carbon provides a method to date pre-historic objects.

    - **Thermal**: A form of energy that is transferred between bodies as a result of their temperature difference. Example: A coffee maker converts the flow of electricity into the flow of *thermal energy*, which it transmits to the water. Note: A pseudo bond graph approach is used here. The true effort and flow variables are temperature and the time rate of change of entropy. However, a more practical pseudo-flow of heat rate is chosen here.

        - **Temperature**: The degree of heat of a body. Example: A coffee maker brings the *temperature* of the water to boiling in order to siphon the water from the holding tank to the filter basket.

        - **Heat rate**: (Note: this is a pseudo-flow) The time rate of change of heat energy of a body. Example: Fins on a motor casing increase the flow *heat rate* from the motor by conduction (through the fin), convection (to the air) and radiation (to the environment).

- **Signal**

    - **Status**: A condition of some system, as in information about the state of the system. Example: Automobiles often measure the engine water temperature and send a *status signal* to the driver via a temperature gage.

        - **Auditory**: A condition of some system as displayed by a sound. Example: Pilots receive an *auditory signal*, often the words "pull up," when their aircraft reaches a dangerously low altitude.

        - **Olfactory**: A condition of some system as related by the sense of smell or particulate count. Example: Carbon monoxide detectors receive an *olfactory signa*l from the environment and monitor it for high levels of CO.

- **Tactile**: A condition of some system as perceived by touch or direct contact. Example: A pager delivers a *tactile signal* to its user through vibration.

- **Taste**: A condition of some dissolved substance as perceived by the sense of taste. Example: In an electric wok, the *taste signal* from the human chef is used to determine when to turn off the wok.

- **Visual**: A condition of some system as displayed by some image. Example: A power screwdriver provides a *visual signal* of its direction through the display of arrows on the switch.

- **Control**: A command sent to an instrument or apparatus to regulate a mechanism. Example: An airplane pilot sends a *control signal* to the elevators through movement of the yoke. The yoke movement is transformed into an electrical signal, sent through wiring to the elevator, and then transformed back into a physical elevator deflection.

  - **Analog**: A control signal sent by direct, continuous, measurable, variable physical quantities. Example: Turning the volume knob on a radio sends an *analog signal* to increase or decrease the sound level.

  - **Discrete**: A control signal sent by separate, distinct, unrelated or discontinuous quantities. Example: A computer sends *discrete signals* to the hard disk controller during read/write operations.

Appendix C3: Application Instructions

Getting Started

This form uses the Functional Basis method to record your functional statements. In this method, a functional statement is represented by a function term, which describes the action being performed, and a flow term, which is what the action is being performed on. These terms are selected from provided lists and together compose the functional statement that will be recorded. To record each functional statement at each level in your functional decomposition hierarchy, there are the following three steps:

1. Select function term
2. Select flow term
3. Add function

Example

Consider the functional statement “adjust base temperature” for a steam iron. The user first selects a function term that most closely matches the term “adjust”, which in this case is the term “change”. Next, the user selects a flow term that most closely matches the term “temperature”. In this case, the term “temperature” is available. The selection of these two terms will be described in greater detail in the help files for each step. The function that is formed by the selected function term and flow term is then added by clicking the “Add Function” button. This process is repeated for each functional statement.

Step 1: Select function term

Using the menus in the three columns below, select a function term that most accurately represents your functional statement. This term describes the action that is being performed. The three columns provide a hierarchy of terms. In order to select a function term, first make a selection from the column of primary functions. If this selection is not precise enough to describe the function, then use the list of secondary functions and (if necessary) tertiary functions to select a more specific function term. If you wish to use a primary or secondary function term, simply leave the remaining columns at the default option, which is “-Select-” or “-N/A-”. The definition of each term that you select is provided in the box on the right that is labeled “Function Description".

Example:

In the case of the functional statement for the steam iron “adjust base temperature”, the desired function term is “adjust”. The primary function with the closest meaning to this term is “Control Magnitude” and would therefore be selected. The closest available function term “change” is then found in the second column and would be selected.

Step 2: Select Flow

Using the menus in the three columns below, select a flow term that most accurately represents what the previously chosen function term is acting on in your functional statement. The three columns provide a hierarchy of terms. In order to select a flow term, first make a selection from the column of primary flows. If this selection is not precise

enough to describe the flow term, then use the list of secondary flow terms and (if necessary) tertiary flow terms to select a more specific term. If you wish to use a primary or secondary flow term, leave the remaining columns at the default option, which is “-Select-“ or “-N/A-” or “-Power Conjugates-”. The definition of each term that you select is provided in the box on the right that is labeled "Flow Description".

Example:
In the case of the functional statement for the steam iron “adjust base temperature”, the desired flow term is “temperature”. The primary flow with the closest meaning to this term is “Energy” and would therefore be selected. The closest available secondary flow term is “Thermal”, which specifies the type of Energy flow. The flow term “temperature” is then available in the column of tertiary flows and is selected.

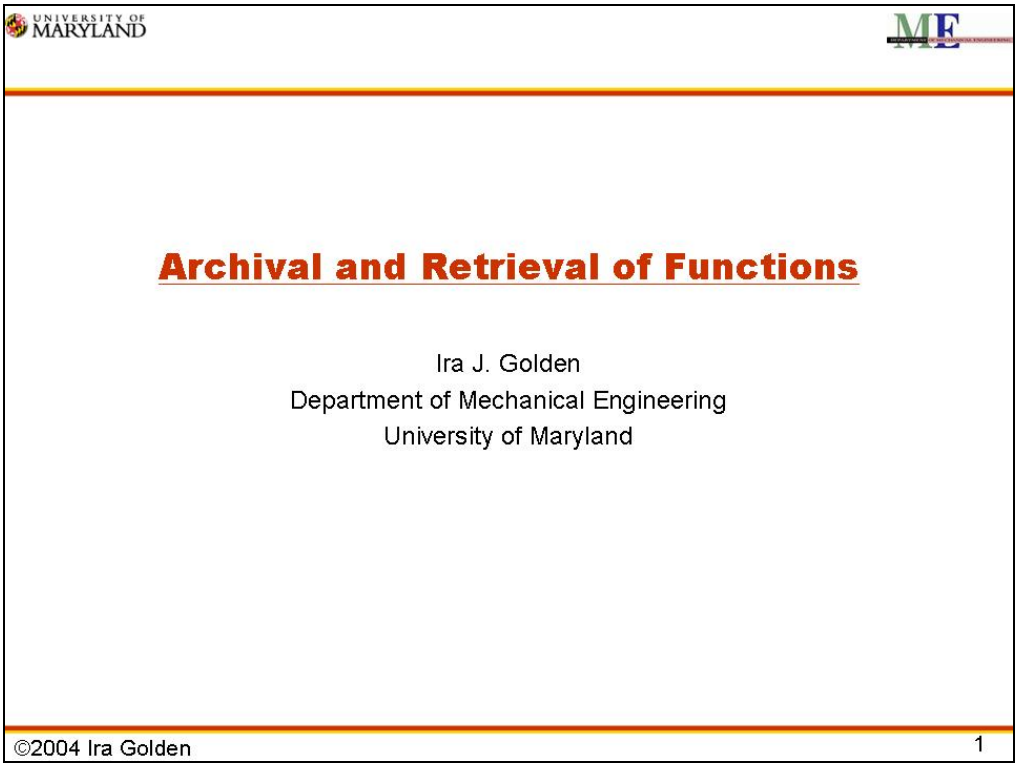
Step 3: Add function
The functional statement formed by the selected function and flow terms will now appear below. If this statement correctly reflects your intended description of the function, you may add the function. First, enter the “Function ID” number that appears in your functional decomposition next to your corresponding function. Then, add the functional statement to the “Function Summary list by clicking the "Add Function" button. If you wish to remove a functional statement from the list, you may do so by selecting the function and then clicking the "Remove Function" button.

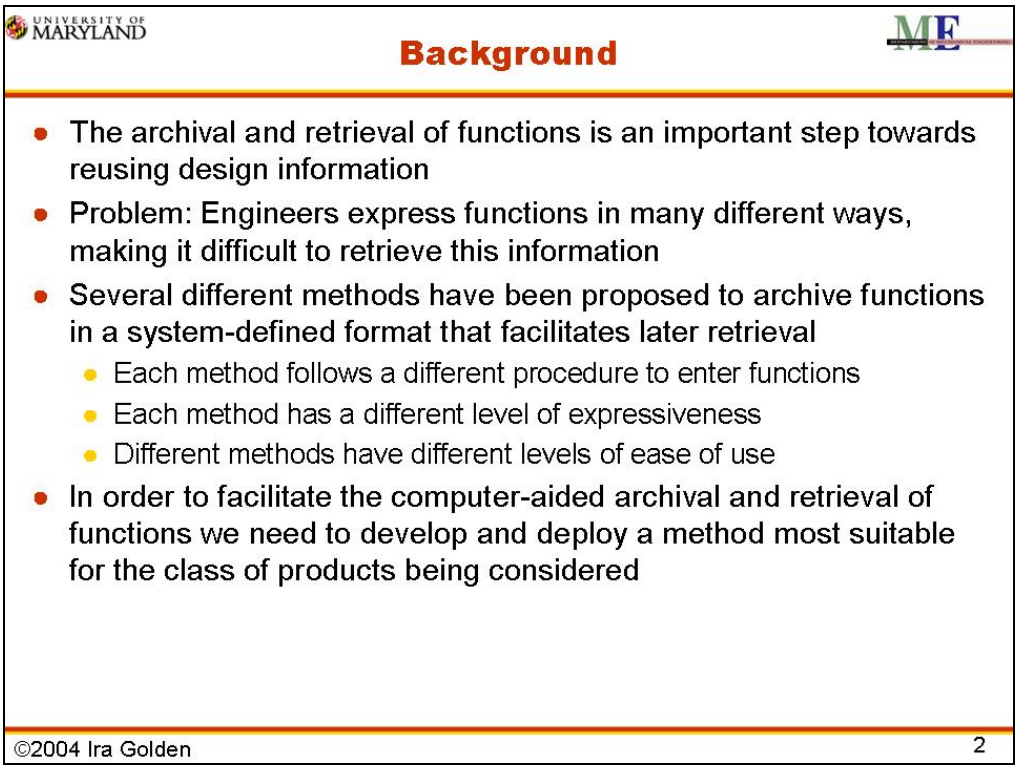
Repeat steps 1-3 for each of the remaining functional statements in your decomposition. After you have added all of your functional statements, submit them by entering your “User ID” number and then clicking the "Submit Functions" button.

Example
In the case of the steam iron, the original functional statement “adjust base temperature” would now appear as “change thermal temperature”. Although awkward, the Functional Basis method requires the secondary flow term “thermal” to modify the tertiary term “temperature”. This function can then be added by entering the unique Function ID number from the functional decomposition and then clicking the “Add Function” button.

Appendix D: User Study

Appendix D1: Tutorial





Field Study

- Objective: Evaluate the usefulness of two methods that are used to record the functions of a product.
  - Functional Basis Method
  - Functional Description Template Method
- Measures
  - Ease of use
  - Correctness
  - Expressiveness
- Steps
  - Identify use environment of product
  - Perform functional decomposition of product
  - For each method, use a web-based application to record the functions of the product from your decomposition

Use Environment

- Use environment: The set of entities and their properties with which the product interacts in its lifetime to carry out its intended functions.
  - Entities: The objects, whether they are physical or non-physical, on which the functions of the product will be acting.
    - External entities: Entities that are present regardless of the design of the product. Commonly inputs or outputs of the system.
    - Internal entities: Entities that describe the product itself or components of the product.
  - Properties: Any relevant quantity or attribute of an entity that may be used in describing the functions of the product.
- The entities and properties in the use environment must be identified because a functional decomposition will describe their interaction with the product.

Example: Ejection mechanism for aircrew

Use environment

- Aircrew
  - Weight, position, horizontal airspeed, vertical airspeed
- Aircraft
  - Volume, horizontal airspeed, vertical airspeed, power output
- Seat
  - Width, position, horizontal airspeed, vertical airspeed
- Services
- Escape path
  - Diameter, location

Functional Decomposition

- A product can be described to perform a single high-level function.
  - The high-level function can be decomposed into several lower-level functions that must be achieved into order to accomplish the high level function.
  - Lower-level functions can be further decomposed several times to create a hierarchy of functions for the product.
- A functional decomposition describes the functional requirements of a product, NOT the design requirements like lightweight, portable, easy to use, etc.
- A functional decomposition allows the engineer to search for solutions that satisfy each of the individual low-level functions.

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Example: Ejection mechanism for aircrew

Functional Decomposition

- FR: Safely eject aircrew from aircraft
  - FR_1: Initiate egress
    - FR_{11}: Initiate ejection
    - FR_{12}: Disconnect aircrew and seat from services
    - FR_{13}: Obtain proper body position
  - FR_2: Aircrew extraction
    - FR_{21}: Create escape path
    - FR_{22}: Separate seat from aircraft
    - FR_{23}: Propel seat through escape path
  - FR_3: Recover aircrew
    - FR_{31}: Orient/stabilize seat and aircrew
    - FR_{32}: Reduce horizontal airspeed
    - FR_{33}: Separate aircrew from seat
    - FR_{34}: Reduce vertical airspeed

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Example: Automatic carton taping system

Use environment

- Carton
  - Volume, weight, orientation, material
- Flaps of carton
  - Width, quantity
- Tape
  - Length, strength
- System
  - Speed

Example: Automatic carton taping system

Functional Decomposition

- FR: Automatically tape cartons
  - FR_1: Place one carton into the system
    - FR_{11}: Orient carton
    - FR_{12}: Propel one carton into the system
  - FR_2: Close the carton's flaps
    - FR_{21}: Maintain orientation of the carton
    - FR_{22}: Close flaps
  - FR_3: Tape carton
    - FR_{31}: Tape carton
    - FR_{32}: Separate tape
  - FR_4: Eject sealed carton from system

Field Study: Part I

- Identify the use environment and functions for a **portable music CD player**.
  1. Randomly select an ID number
  2. Create a new word document, named "Functions(ID)", where "ID" is the number that you have chosen.
  3. Define the use environment for the CD player
     - Type up all entities, external and internal, and their relevant properties
  4. Perform a functional decomposition for the CD player
     - Perform three levels of decomposition
     - Approximately 12-15 low-level functions are expected.
     - Assign a unique number to each function
  5. Save your document and FTP the file to the following address:
     - IP address:
     - Port:
     - Login: upload
     - Password: upload

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Example: Steam Iron

- Consider, for example, a **steam iron**
- What are the entities in the use environment for the steam iron.
  - External?
  - Internal?
- What are the relevant properties of these entities?

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Example: Steam Iron

- External entities/properties
  - User
  - Clothing
    - Material, wrinkles, pressure
  - Water
    - Temperature, volume
  - Steam
    - Temperature, velocity
  - Heat
  - Power source
  - Electrical energy
- Internal entities/properties
  - Iron
    - Weight
  - Switch
    - Location
  - Base
    - Surface area, temperature

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Example: Steam Iron

- What functions must the steam iron perform?
  - High level?
  - Lower levels?
- FR: Smooth out wrinkles in clothing
  - FR_1: Maintain uniform base temperature
    - FR_{11}: Generate heat
    - FR_{12}: Adjust base temperature
  - FR_2: Generate steam
    - FR_{21}: Store water
    - FR_{22}: Generate steam
    - FR_{23}: Facilitate addition of water
  - FR_3: Exert pressure on clothing

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Field Study: Part II

- Record functions online using two web-based applications
  - Instructions shown below and the two website locations will be emailed out once everyone has submitted Part I.
- Instructions
  - Record each of the functions from your functional decomposition **in the order they appear in the decomposition**.
  - Also record the number that identifies each function
  - Instructions for both applications can be accessed from "Help?" links throughout the forms.
  - When recording each function from your decomposition . . .
    - Enter or select the terms that most accurately represent the function that you originally typed.
    - If you feel you are unable to record a function that retains your intended meaning, then skip that function.

Appendix D2: Part I Instructions

Part I – Identify the use environment and functions for a **portable music CD player**.

1. Create a new word document, named "Functions(ID)", where "ID" is the number that you chose during the tutorial.

2. Define the use environment for the CD player by typing up all of the entities, both external and internal, and their relevant properties. These entities and properties will be used in your functional decomposition. You are to perform this step before the functional decomposition; however, you may go back and add entities and properties used in the decomposition, once completed.

3. Then, type up a functional decomposition for the CD player for three levels of decomposition. The number of functions may vary for each person, but approximately 5-6 second-level functions and 12-15 third-level functions are expected. Make sure to assign a unique identification number to each function in the decomposition.

4. Save your document that is named "Functions(ID)" and send the file via FTP to the following address:

- IP address: _ _ _ . _ _ _ . _ _ _ . _ _ _
- Port: _ _
- Login: upload
- Password: upload

5. Once I have received everyone's files, I will email out instructions for Part II and Part III.

Appendix D3: Part II and Part III Instructions

Part II - Record functions online using two web-based applications

Using the two web-based applications that are listed below, you are to record each of the functions from your functional decomposition, along with their ID numbers, **in the order they appear in your decomposition**. Your objective is to enter or select the terms that most accurately represent the function that you originally typed, even if changes have to be made. Despite these changes, if you feel that you are unable to record your functional statement in a way that retains its basic meaning then skip that function. Be sure to read the instructions for both applications that are provided through the "Help?" links that appear throughout the applications. These help files will explain all the necessary steps and provide an example.

- http://www.bioinspired.umd.edu/basis
- http://www.bioinspired.umd.edu/template

Part III – Evaluations

After completing both forms, rename this document file to "Evaluations(ID)", where "ID" is the number that you chose during the tutorial. Answer the questions below by deleting all available choices except the one that is your answer. For example, if your answer is option c, then delete options a,b,d, and e. Save this document and FTP the file to the following address:

- IP address: _ _ _ . _ _ _ . _ _ _ . _ _ _
- Port: _ _
- Login: upload
- Password: upload

4. In both methods, you were required to select terms from provided lists. On average for all of your functional statements, in which of the two methods was it easier to locate the terms that you were seeking?

    a) Functional Description Template was much easier.
    b) Functional Description Template was a little bit easier.
    c) Both methods were about the same.
    d) Functional Basis was a little bit easier.
    e) Functional Basis was much easier.

5. In both methods, you were asked to record your functions as close as possible to how you originally typed them. On average for all of your functional statements, which method recorded functions that most accurately represented the functions you had originally typed?

    a) Functional Description Template was much more accurate.

b) Functional Description Template was a little bit more accurate.
c) Both methods were about the same.
d) Functional Basis was a little bit more accurate.
e) Functional Basis was much more accurate.

6. Please add any comments regarding the use of these two methods.

Appendix D4: Author's Solution

Use Environment (Entities and properties)

External

- User
- Disc
  - Diameter
  - Position
  - Rotational speed
- Data
- Power source
- Electrical energy
- Music
  - Volume

Internal

- CD player
  - Weight
  - Volume
- Laser
- Light
  - Intensity
- Mechanical energy

Functional Decomposition

- FR: Play music from a disc
  - FR_1: Supply power
    - FR_{11}: Provide electrical energy
    - FR_{12}: Convert electrical energy to mechanical energy
    - FR_{13}: Convert electrical energy to light
  - FR_2: Contain disc
    - FR_{21}: Receive disc
    - FR_{22}: Secure position of disc
    - FR_{23}: Enclose disc
  - FR_3: Read data from disc
    - FR_{31}: Generate light from laser
    - FR_{32}: Focus light onto disc
    - FR_{33}: Rotate disc
    - FR_{34}: Regulate rotational speed of disc
    - FR_{35}: Move laser
    - FR_{36}: Convert data to electrical signal
  - FR_4: Control CD player
    - FR_{41}: Start reading data
    - FR_{42}: Adjust volume of music
    - FR_{43}: Select track on disc
  - FR_5: Release disc

Functional Basis: Recorded functions

- FR: Supply auditory signal
  - FR_1: Supply electrical energy
    - FR_{11}: Supply electrical energy
    - FR_{12}: Convert electrical energy
    - FR_{13}: Convert electrical energy
  - FR_2: Contain object material
    - FR_{21}: Import object material
    - FR_{22}: Secure object material
    - FR_{23}: Contain object material
  - FR_3: Detect discrete signal
    - FR_{31}: Actuate optical energy
    - FR_{32}: Guide optical energy
    - FR_{33}: Rotate object material
    - FR_{34}: Regulate rotational energy
    - FR_{35}: Transport object material
    - FR_{36}: Convert discrete signal
  - FR_4: Regulate object material
    - FR_{41}: Process discrete signal
    - FR_{42}: Regulate acoustic energy
    - FR_{43}: Change discrete signal
  - FR_5: Export object material

Functional Description Template

Entity and property classifications

- Disc (Object)
  - Location (Motion property)
  - Angular velocity (Motion property)
- Data (Audio data)
- Power source (Device)
- Electrical energy (Electrical energy)
- Music (Sound wave)
  - Amplitude (Waves property)
- CD player (Device)
- Laser (Device)
- Light (Electromagnetic wave)
  - Intensity (Mechanics property)
- Mechanical energy (Mechanical energy)

Recorded functions (Action classification appears in parentheses)

- FR: Play (Start) music from disc
  - FR_1: Supply (Provide) electrical energy from power source
    - FR_{11}: Provide electrical energy
    - FR_{12}: Convert (Change) electrical energy to mechanical energy
    - FR_{13}: Convert (Change) electrical energy to light

- FR_2: Contain disc
  - FR_{21}: Receive (Acquire) disc
  - FR_{22}: Secure location of disc
  - FR_{23}: Enclose (Contain) disc
- FR_3: Read (Detect) data from disc
  - FR_{31}: Generate (Create) light from laser
  - FR_{32}: Focus (Guide) light onto disc
  - FR_{33}: Rotate disc
  - FR_{34}: Regulate (Change) angular velocity of disc
  - FR_{35}: Move laser
  - FR_{36}: Convert (Change) data to electrical energy
- FR_4: Control (Guide) CD player
  - FR_{41}: Start CD player
  - FR_{42}: Adjust (Change) amplitude of music
  - FR_{43}: Select (Specify) data on disc
- FR_5: Release (Eject) disc

Appendix D5: Functional Basis User Response Data

				Functional Basis			
User ID	**Func ID**	**Func #**	**Orginal Functions**	**Functions**	**Correct**	**Matches**	**Lost Info**
101	1	1	Play a CD in a portable manner	Process Object Material	P	0	1
101	1.1	2	Operate Laser Read Head using Power	Actuate Object Material	Y	0	1
101	1.1.1	3	Transfer electricity from power source to laser	Convert Electrical Energy	P	1	2
101	1.1.2	4	Regulate power level to laser	Regulate Electrical Energy	Y	1	1
101	1.2	5	Read CD surface with Laser Read Head	Sense Object Material	Y	0	1
101	1.2.1	6	Move Laser Read Head over CD surface	Actuate Object Material	Y	0	1
101	1.2.2	7	Send read data to CPU	Export Analog Signal	P	0	1
101	1.3	8	Convert Read data to Sound Output	Convert Analog Signal	P	1	1
101	1.3.1	9	Get read data from CPU	Import Analog Signal	P	0	1
101	1.3.2	10	Convert data into audio format	Convert Analog Signal	P	1	1
101	1.3.3	11	Send audio data to sound output	Export Analog Signal	P	0	1
101	1.4	12	Regulate Sound Output levels	Regulate Acoustic Energy	Y	1	0
101	1.4.1	13	Prevent volume from going past a threshold level	Prevent Acoustic Energy	Y	1	2
101	1.4.2	14	Use volume button inputs to raise or lower volume level	Detect Discrete Signal	N	0	4
101	1.5	15	Allow User to input desires		N	0	4
101	1.5.1	16	Convert buttons pushed to electric signals	Convert Discrete Signal	Y	2	1
101	1.5.2	17	Send electrical signals to CPU	Transmit Electrical Energy	Y	0	1
101	1.5.3	18	Send volume button input to sound regulation	Transmit Analog Signal	Y	0	1
102	0	1	Play CDs using own power source.	Convert Auditory Signal	N	0	1
102	1	2	Spin CD	Rotate Object Material	Y	0	0
102	11	3	Facilitate installation of CD	Join Object Material	P	0	0
102	12	4	Secure CD	Secure Object Material	Y	1	0
102	13	5	Rotate CD at optimal RPM	Regulate Object Material	P	0	1
102	2	6	Provide anti-skip protection	Stabilize Signal	N	0	0
102	21	7	Store data	Collect Signal	Y	0	0
102	22	8	Sense a skip in the CD	Detect Signal	Y	0	1

				Functional Basis			
User ID	Func ID	Func #	Orginal Functions	Functions	Correct	Matches	Lost Info
102	23	9	Replace missing data	Process Signal	P	0	0
102	3	10	Convert to sound	Convert Signal	Y	1	0
102	31	11	Receive data from CD	Collect Analog Signal	P	0	1
102	32	12	Convert to sound	Convert Signal	Y	1	0
102	4	13	Broadcast sound	Distribute Signal	Y	0	0
102	41	14	Amplify sound	Process Signal	P	0	0
102	42	15	Transfer sound to speakers	Transmit Auditory Signal	Y	0	1
102	43	16	Focus sound to user	Channel Auditory Signal	Y	0	1
102	5	17	Use portable power source	Convert Electrical Energy	P	0	1
102	51	18	Generate DC electrical energy	Supply Electrical Energy	Y	2	0
102	52	19	Facilitate replacement of power source	Remove Electrical Energy	Y	0	0
102	6	20	Read data from CD	Detect Analog Signal	P	0	1
102	61	21	Focus laser	Channel Electrical Energy	P	0	0
102	62	22	Transmit data	Transmit Signal	Y	1	0
103	0	1	Play a song	Export Acoustic Energy	P	0	0
103	1	2	Place disk into the system	Import Solid-solid Material	Y	0	1
103	11	3	Open lid	Divide Object Material	Y	0	0
103	12	4	Fix disk onto disk drive	Secure Solid-solid Material	Y	0	1
103	13	5	Close lid	Join Object Material	Y	0	0
103	2	6	Select track	Sense Object Material	P	0	0
103	21	7	Spin the disc at a certain velocity	Rotate Solid-solid Material	Y	0	1
103	22	8	Position laser system and optoelectronic system at the beginning of the selected track	Transport Solid-solid Material	P	0	3
103	3	9	Read track	Convert Object Material	P	0	0
103	31	10	Focus laser system and optoelectronic system on the track	Transport Solid-solid Material	N	0	2
103	32	11	Emit beam	Supply Optical Intensity	P	0	0
103	33	12	Convert reflected beam into digital signal	Convert Optical Intensity	P	1	1
103	34	13	Convert digital signal into analogical signal	Convert Discrete Signal	Y	2	1
103	35	14	Move the laser system and optoelectronic system to follow the track	Transport Solid-solid Material	P	0	3

				Functional Basis			
User ID	**Func ID**	**Func #**	**Orginal Functions**	**Functions**	**Correct**	**Matches**	**Lost Info**
103	36	15	Adjust spin velocity of the disc	Condition Rotational Angular velocity	Y	1	1
103	4	16	Emit sound	Export Acoustic Energy	Y	0	0
103	41	17	Amplify analogical signal	Increase Analog Signal	Y	2	0
103	42	18	Emit sound from the headphones	Export Acoustic Energy	Y	0	1
104	0	1	Play the sound tracks on the CD	Convert Discrete Signal	P	0	1
104	1	2	Load / hold / eject the CD	Contain Object Material	Y	0	0
104	11	3	Accept a CD	Import Object Material	Y	0	0
104	12	4	Lock the CD to the axle of the spinning motor	Secure Object Material	Y	0	2
104	13	5	Release the CD	Export Object Material	Y	0	0
104	2	6	Read the sound tracks from the CD	Sense Discrete Signal	Y	0	1
104	21	7	Spin the CD	Rotate Object Material	Y	0	0
104	22	8	Move the optical receiver along the radial direction of the CD	Translate Object Material	Y	0	2
104	23	9	Read the data on the CD	Sense Discrete Signal	Y	0	1
104	3	10	Convert the digital readout to audio signal	Convert Discrete Signal	Y	2	1
104	31	11	Decode the digital readout	Process Discrete Signal	Y	0	0
104	32	12	Buffer data for anti-shock	Contain Discrete Signal	Y	0	1
104	33	13	D/A conversion	Convert Discrete Signal	Y	1	1
104	34	14	Signal amplification	Increase Analog Signal	Y	1	0
104	4	15	Display the play mode and sound track information	Display Visual Signal	Y	1	1
104	41	16	Read the play mode and other sensor information (battery life, etc)	Sense Control Signal	Y	0	1
104	42	17	Display the information on the LCD screen	Display Visual Signal	Y	1	1
104	5	18	Accept user control and take action	Sense Status Signal	Y	0	1
104	51	19	Sense the user input from the buttons and knobs	Sense Object Material	P	1	1
104	52	20	Take appropriate action as response	Process Control Signal	Y	0	0
201	1	1	Play music on CD	Transmit Auditory Signal	Y	0	1
201	11	2	Rotate Disc	Rotate Object Material	Y	1	0
201	111	3	Hold Disc	Stabilize Object Material	P	0	0

				Functional Basis			
User ID	Func ID	Func #	Orginal Functions	Functions	Correct	Matches	Lost Info
201	112	4	Convert electrical energy to rotational energy	Convert Electrical Current	P	2	1
201	113	5	Maintain constant speed	Stabilize Rotational Angular velocity	Y	0	0
201	12	6	Read disc	Measure Discrete Signal	N	0	0
201	121	7	Keep laser steady	Position Object Material	P	0	0
201	122	8	Translate laser	Translate Object Material	Y	1	0
201	123	9	Convert electrical energy to light	Convert Optical Energy	P	2	1
201	124	10	Move laser		N	0	2
201	125	11	Focus laser	Condition Optical Intensity	P	0	0
201	13	12	Process Data	Process Discrete Signal	Y	1	0
201	131	13	Receive reflected light	Collect Optical Energy	Y	0	0
201	14	14	Convert data	Convert Discrete Signal	Y	1	0
201	141	15	Convert reflected light to electrical energy	Convert Optical Energy	Y	2	1
201	15	16	Amplify	Increase Electrical Energy	Y	0	0
201	151	17	Increase amplitude of waves	Increase Electrical Current	P	1	0
201	16	18	Output amplified sound	Distribute Auditory Signal	Y	0	0
201	161	19	Transport sound	Transmit Acoustic Energy	Y	0	0
201	162	20	Convert amplified waves to sound	Convert Acoustic Energy	Y	1	1
201	17	21	Keep user safe		N	0	2
201	171	22	Block laser from user	Prevent Optical Energy	Y	0	1
201	172	23	Keep spinning CD away from user	Prevent Object Material	P	0	1
201	173	24	Insulate to avoid electric shock	Prevent Electrical Current	Y	1	0
201	18	25	Support the structure	Secure Object Material	Y	0	0
201	181	26	Keep power source contained	Secure Electrical Energy	P	0	0
201	182	27	Fix positions of parts	Secure Object Material	Y	0	0
202	0	1	Play CDs	Signal Acoustic Energy	P	0	0
202	1	2	Load CD	Position Material	Y	0	0
202	11	3	Open CD housing	Secure Material	P	0	0
202	12	4	Position CD on spinning mechanism	Stabilize Material	P	0	1
202	2	5	Transport CD	Transport Material	Y	1	0
202	21	6	Portable housing	Allow DOF Material	P	0	0
202	22	7	Latch CD housing closed	Secure Object Material	Y	0	0

				Functional Basis			
User ID	Func ID	Func #	Orginal Functions	Functions	Correct	Matches	Lost Info
202	3	8	Power Device	Supply Energy	Y	0	0
202	31	9	Switch ON	Convert Control Signal	Y	0	0
202	32	10	Supply battery power	Supply Electrical Energy	Y	1	0
202	4	11	Read CD	Detect Material	Y	0	0
202	41	12	Spin CD	Actuate Material	P	0	0
202	42	13	Project laser eye to CD surface	Sense Signal	N	0	1
202	5	14	Display statistics	Display Signal	Y	1	0
202	51	15	Read track data	Measure Auditory Signal	P	0	0
202	52	16	Print track data on LCD screen	Track Auditory Signal	N	1	1
202	6	17	Transmit Sound	Export Auditory Signal	Y	0	0
202	61	18	Interpret laser eye readings	Process Auditory Signal	P	0	0
202	62	19	Convert to audio	Convert Auditory Signal	P	2	0
202	63	20	Adjust volume	Regulate Auditory Signal	Y	0	0
202	64	21	Connect to headphones	Link Auditory Signal	P	0	0
203	0	1	Play a music CD		N	0	2
203	1	2	Open cd payer		N	0	2
203	1a	3	Move latch to open lid	Translate Object Material	Y	0	1
203	2	4	Insert cd		N	0	2
203	2a	5	Snap cd onto cd holder	Link Object Material	Y	0	1
203	3	6	Close cd player		N	0	2
203	3a	7	Close lid such that latch engages to hold lid closed	Position Object Material	Y	0	2
203	4	8	Spin up cd		N	0	2
203	4a	9	Activate motor	Actuate Analog Signal	P	0	0
203	4b	10	Ensure motor spins to proper rpm	Measure Analog Signal	P	0	1
203	5	11	Align laser		N	0	2
203	5a	12	Move laser with screw drive	Translate Object Material	Y	0	1
203	5b	13	Align laser with track on cd	Position Object Material	Y	0	1
203	6	14	Play music		N	0	2
203	6a	15	Read data from cd	Detect Visual Signal	Y	0	1
203	6b	16	Continuously move laser to stay aligned with track on cd	Translate Object Material	Y	0	2

				Functional Basis			
User ID	Func ID	Func #	Orginal Functions	Functions	Correct	Matches	Lost Info
203	7	17	Stop cd		N	0	2
203	7a	18	Stop motor from spinning	Stop Object Material	Y	1	0
203	8	19	Open cd player		N	0	2
203	8a	20	Move latch to open lid	Translate Object Material	Y	0	1
203	9	21	Remove cd		N	0	2
203	9a	22	Snap cd off of cd holder	Remove Object Material	Y	0	1
203	10	23	Close cd player		N	0	2
203	10a	24	Close lid such that latch engages to hold lid closed	Secure Object Material	Y	0	2
205	0	1	Play music	Process Auditory Signal	Y	0	0
205	1	2	Accept CD	Position Composite Material	P	0	0
205	1a	3	Open compartment	Import Composite Material	N	0	0
205	1b	4	Insert CD	Transport Composite Material	Y	0	0
205	1c	5	Close compartment	Secure Composite Material	P	0	0
205	2	6	Read CD	Detect Optical Intensity	P	0	0
205	2a	7	Drive motor spins CD	Rotate Composite Material	Y	0	1
205	2b	8	Focus laser onto CD	Position Optical Energy	Y	0	1
205	2c	9	Photodiode captures laser reflectance	Measure Optical Intensity	Y	0	1
205	3	10	Play Music	Process Optical Intensity	P	0	0
205	3a	11	Convert photodiode signal to audio	Convert Optical Energy	P	1	1
205	3b	12	Send output to headphones	Display Auditory Signal	P	0	1
205	4	13	Edit sound	Regulate Auditory Signal	Y	0	0
205	4a	14	Skip tracks	Condition Auditory Signal	Y	0	0
205	4b	15	Increase volume	Regulate Auditory Signal	P	0	0
205	4c	16	Pause music	Prevent Auditory Signal	Y	0	0
205	4d	17	Fast Forward music	Increment Auditory Signal	Y	0	0
205	4e	18	Rewind music	Decrement Auditory Signal	Y	0	0
205	5	19	Eject CD	Extract Composite Material	Y	0	0
205	5a	20	Press eject button	Position Tactile Signal	P	0	0
205	5b	21	Open compartment	Translate Object Material	Y	0	0
205	5c	22	Extract CD	Remove Composite Material	Y	0	0
302	0	1	Play Music		N	0	2

				Functional Basis			
User ID	**Func ID**	**Func #**	**Orginal Functions**	**Functions**	**Correct**	**Matches**	**Lost Info**
302	1	2	Load CD	Collect Object Material	P	0	0
302	11	3	Allow for placement of CD	Import Object Material	Y	0	0
302	12	4	Contain CD	Position Object Material	P	0	0
302	13	5	Protect CD from outside elements		N	0	3
302	14	6	Allow for removal of CD	Remove Object Material	Y	1	0
302	2	7	Read Data from CD	Collect Discrete Signal	P	0	1
302	21	8	Rotate CD	Actuate Rotational Angular velocity	N	1	0
302	22	9	Allow for track selection	Process Control Signal	Y	0	0
302	23	10	Gather optical data	Measure Optical Energy	P	1	0
302	24	11	Convert optical data to analog electrical signals	Convert Optical Energy	Y	2	1
302	3	12	Output data	Supply Analog Signal	Y	0	0
302	31	13	Send signal to speakers	Export Analog Signal	Y	1	1
302	32	14	Convert signal to magnetic fields	Convert Analog Signal	Y	2	1
302	33	15	Convert magnetic fields to acoustic waves	Convert Electromagnetic Energy	Y	2	1
302	4	16	Provide power	Supply Electrical Energy	Y	0	0
302	5	17	Allow user to turn entire device on/off	Change Status Signal	Y	0	3
305	1	1	Plays audio CDs		N	0	2
305	1.1	2	Get power	Connect Electrical Energy	P	0	0
305	1.1.1	3	Put on the ear plugs/head phones		N	0	2
305	1.1.2	4	Connect power cable if necessary and turn on the power mode	Connect Electrical Current	Y	1	2
305	1.2	5	Insert a CD	Connect Object Material	P	0	0
305	1.2.1	6	Open the lid to insert CD or just press the insertion button		N	0	6
305	1.2.2	7	Place the CD on the slot		N	0	3
305	1.2.3	8	Close the lid or press the insertion done button		N	0	4
305	1.3	9	Play a CD		N	0	2
305	1.3.1	10	Press the play button		N	0	2
305	1.3.2	11	CD starts playing	Convert Electrical Energy	N	0	0
305	1.3.3	12	Enjoy the music	Sense Acoustic Energy	Y	0	0

				Functional Basis			
User ID	**Func ID**	**Func #**	**Orginal Functions**	**Functions**	**Correct**	**Matches**	**Lost Info**
305	1.4	13	Pause/Stop playing a CD		N	0	2
305	1.4.1	14	Press the pause/stop button		N	0	2
305	1.4.2	15	CD stops playing		N	0	2
305	1.5	16	Remove the CD		N	0	2
305	1.5.1	17	Open the lid or press eject button		N	0	4
305	1.5.2	18	Take out the CD		N	0	2
305	1.5.3	19	Close the lid or press ejection done button		N	0	4
305	1.6	20	Turn off power		N	0	2
305	1.6.1	21	Press the power button once again to stop getting power anymore and disconnect power cables if required		N	0	6
305	1.6.2	22	Take off the ear plugs/head phones		N	0	2
306	1	1	Play music from a CD	Actuate Object Material	P	0	1
306	11	2	Provide mechanism for mounting and ejecting CD's	Channel Object Material	Y	0	3
306	111	3	Open CD compartment	Actuate Object Material	Y	0	0
306	112	4	Mount/Remove CD	Position Object Material	Y	0	0
306	113	5	Close CD compartment	Stop Object Material	P	0	0
306	12	6	Select track information		N	0	2
306	121	7	Select track		N	0	2
306	122	8	Spin CD at specific angular velocity	Control Magnitude Object Material	P	0	1
306	13	9	Play CD	Actuate Object Material	P	0	0
306	131	10	Read track data using CD track reader		N	0	3
306	132	11	Convert rotational energy into signal using data	Convert Rotational Energy	Y	3	2
306	133	12	Transport signal to headphones	Transport Signal	Y	2	1
306	134	13	Convert signal into sound energy using headphones	Convert Signal	Y	2	2
306	14	14	Display track information		N	0	2
306	141	15	Read track data using CD track reader		N	0	3
306	142	16	Convert electrical energy from battery to light energy to display track data	Convert Electrical Energy	Y	3	4

				Functional Basis			
User ID	Func ID	Func #	Orginal Functions	Functions	Correct	Matches	Lost Info
307	1	1	Output Sound	Export Acoustic Energy	Y	0	0
307	11	2	Hold CD	Secure Object Material	Y	0	0
307	111	3	Orient CD in proper position	Position Object Material	Y	1	1
307	112	4	Prevent CD face from being scratched	Stabilize Object Material	P	0	1
307	12	5	Spin CD	Actuate Rotational Energy	N	0	0
307	121	6	Spin at correct RPM	Regulate Rotational Energy	Y	0	0
307	122	7	Hold CD for rotation	Secure Rotational Energy	P	1	1
307	123	8	Keep CD face planar	Stabilize Rotational Energy	P	0	0
307	13	9	Read CD	Process Signal	N	0	0
307	131	10	Laser watts	Regulate Optical Intensity	Y	0	0
307	132	11	Move CD over laser	Regulate Rotational Angular velocity	N	0	1
307	14	12	Eject CD	Separate Material	Y	0	0
307	141	13	Initiate ejection	Actuate Material	P	0	0
307	142	14	Prevent CD face from being scratched	Stabilize Material	P	0	1
307	15	15	Output Sound	Export Electrical Energy	P	0	0
307	151	16	Adjust Volume	Regulate Acoustic Energy	Y	0	0
307	152	17	Transmit to speakers	Export Acoustic Energy	Y	0	1
307	16	18	Portability	Transfer Material	Y	0	0
307	161	19	Weight	Control Magnitude Human Force	N	0	0
307	162	20	Size	Control Magnitude Object Material	N	0	0
307	163	21	Skip prevention	Stabilize Auditory Signal	N	0	0

Appendix D6: Functional Description Template User Response Data

				Functional Description Template			
User ID	**Func ID**	**Func #**	**Orginal Functions**	**Functions**	**Correct**	**Matches**	**Lost Info**
101	1	1	Play a CD in a portable manner	Play CD	Y	2	1
101	1.1	2	Operate Laser Read Head using Power	Operate Laser Read Head using Power (Electricity)	Y	5	0
101	1.1.1	3	Transfer electricity from power source to laser	Transfer Power (Electricity) to Laser Read Head	Y	3	1
101	1.1.2	4	Regulate power level to laser	Regulate Power (Electricity) to Laser Read Head	Y	3	0
101	1.2	5	Read CD surface with Laser Read Head	Read CD with Laser Read Head	Y	5	0
101	1.2.1	6	Move Laser Read Head over CD surface	Move Laser Read Head over CD	Y	5	0
101	1.2.2	7	Send read data to CPU	Send Read Data to CPU	Y	4	0
101	1.3	8	Convert Read data to Sound Output	Convert Read Data to Sound Output	Y	5	0
101	1.3.1	9	Get read data from CPU	Get Read Data from CPU	Y	4	0
101	1.3.2	10	Convert data into audio format	Convert Read Data	Y	2	1
101	1.3.3	11	Send audio data to sound output	Send Sound Output	Y	3	1
101	1.4	12	Regulate Sound Output levels	Regulate Sound Output	Y	3	0
101	1.4.1	13	Prevent volume from going past a threshold level	Prevent Sound Output	Y	1	2
101	1.4.2	14	Use volume button inputs to raise or lower volume level	Detect Buttons	N	1	3
101	1.5	15	Allow User to input desires	Allow User	Y	2	2
101	1.5.1	16	Convert buttons pushed to electric signals	Convert Buttons to Power (Electricity)	Y	3	0
101	1.5.2	17	Send electrical signals to CPU	Send Power (Electricity) to CPU	Y	3	0
101	1.5.3	18	Send volume button input to sound regulation	Send Sound Output to Sound Output	P	2	0
102	0	1	Play CDs using own power source.	Play CDs using Power Source	Y	5	0
102	1	2	Spin CD	Spin CDs	Y	2	0
102	11	3	Facilitate installation of CD	Insert CDs	Y	1	0
102	12	4	Secure CD	Secure CDs	Y	2	0
102	13	5	Rotate CD at optimal RPM	Spin CDs	Y	1	1

				Functional Description Template			
User ID	**Func ID**	**Func #**	**Orginal Functions**	**Functions**	**Correct**	**Matches**	**Lost Info**
102	2	6	Provide anti-skip protection	Provide Memory	Y	1	0
102	21	7	Store data	Store Memory	P	1	0
102	22	8	Sense a skip in the CD	Sense Memory	P	1	1
102	23	9	Replace missing data	Insert Memory	P	0	0
102	3	10	Convert to sound	Convert Sound	Y	2	0
102	31	11	Receive data from CD	Receive CDs	P	2	1
102	32	12	Convert to sound	Convert Sound	Y	2	0
102	4	13	Broadcast sound	Play Sound	P	1	0
102	41	14	Amplify sound	Amplify Sound	Y	2	0
102	42	15	Transfer sound to speakers	Transfer Sound to Speakers	Y	3	0
102	43	16	Focus sound to user	Focus Sound to User	Y	3	0
102	5	17	Use portable power source	Use Power Source	Y	3	1
102	51	18	Generate DC electrical energy		N	0	2
102	52	19	Facilitate replacement of power source	Remove Power Source	Y	2	0
102	6	20	Read data from CD	Collect Sound from CDs	P	1	0
102	61	21	Focus laser	Focus Laser	Y	2	0
102	62	22	Transmit data	Communicate Sound	P	0	0
103	0	1	Play a song	Play sound	Y	1	0
103	1	2	Place disk into the system	Insert compact disk into CD player	Y	1	0
103	11	3	Open lid	Open lid	Y	2	0
103	12	4	Fix disk onto disk drive	Fix compact disk onto disk drive	Y	4	0
103	13	5	Close lid	Close lid	Y	2	0
103	2	6	Select track	Select spiral tracks	P	2	0
103	21	7	Spin the disc at a certain velocity	Spin compact disk	Y	2	1
103	22	8	Position laser system and optoelectronic system at the beginning of the selected track	Place laser system	Y	2	3
103	3	9	Read track	Read spiral tracks	P	2	0
103	31	10	Focus laser system and optoelectronic system on the track	Focus laser system on spiral tracks	Y	4	1
103	32	11	Emit beam	Emit beam	Y	2	0
103	33	12	Convert reflected beam into digital signal	Convert beam into digital signal	Y	4	0

				Functional Description Template			
User ID	**Func ID**	**Func #**	**Orginal Functions**	**Functions**	**Correct**	**Matches**	**Lost Info**
103	34	13	Convert digital signal into analogical signal	Convert digital signal into analogic signal	Y	5	0
103	35	14	Move the laser system and optoelectronic system to follow the track	Move laser system along spiral tracks	Y	4	1
103	36	15	Adjust spin velocity of the disc		N	0	3
103	4	16	Emit sound	Emit sound	Y	2	0
103	41	17	Amplify analogical signal	Amplify analogic signal	Y	3	0
103	42	18	Emit sound from the headphones	Emit sound from headphones	Y	3	0
104	0	1	Play the sound tracks on the CD	Convert Sound Tracks on CD to Audio Signal	P	3	0
104	1	2	Load / hold / eject the CD	Keep CD	Y	1	0
104	11	3	Accept a CD	Accept CD	Y	2	0
104	12	4	Lock the CD to the axle of the spinning motor	Lock CD	Y	2	2
104	13	5	Release the CD	Eject CD	Y	1	0
104	2	6	Read the sound tracks from the CD	Convert Sound Tracks on CD to Digital Readout	P	3	0
104	21	7	Spin the CD	Spin CD	Y	2	0
104	22	8	Move the optical receiver along the radial direction of the CD	Translate Optical Pickup	Y	1	2
104	23	9	Read the data on the CD	Convert Sound Tracks on CD to Digital Readout	P	1	0
104	3	10	Convert the digital readout to audio signal	Convert Digital Readout to Audio Signal	Y	5	0
104	31	11	Decode the digital readout	Convert Digital Readout	Y	2	0
104	32	12	Buffer data for anti-shock	Cache Digital Readout	Y	0	1
104	33	13	D/A conversion	Convert Digital Readout to Audio Signal	Y	1	0
104	34	14	Signal amplification	Amplify Audio Signal	Y	2	0
104	4	15	Display the play mode and sound track information	Output Status of CD Player to LCD Screen	Y	0	1

				Functional Description Template			
User ID	**Func ID**	**Func #**	**Orginal Functions**	**Functions**	**Correct**	**Matches**	**Lost Info**
104	41	16	Read the play mode and other sensor information (battery life, etc)	Check Status of CD Player	Y	0	1
104	42	17	Display the information on the LCD screen	Output Status of CD Player to LCD Screen	Y	2	0
104	5	18	Accept user control and take action	Accept User Operation from User Control Pannel	Y	3	1
104	51	19	Sense the user input from the buttons and knobs		N	0	3
104	52	20	Take appropriate action as response		N	0	2
201	1	1	Play music on CD	Produce sound	Y	0	1
201	11	2	Rotate Disc	Rotate disc	Y	2	0
201	111	3	Hold Disc	Hold disc	Y	2	0
201	112	4	Convert electrical energy to rotational energy	Convert electrical power	Y	2	1
201	113	5	Maintain constant speed	Maintain Frequency of motor	P	1	0
201	12	6	Read disc	Read disc	Y	2	0
201	121	7	Keep laser steady	Steady laser	Y	2	0
201	122	8	Translate laser	Translate laser	Y	2	0
201	123	9	Convert electrical energy to light	Convert electrical power	Y	2	1
201	124	10	Move laser	Move laser	Y	2	0
201	125	11	Focus laser	Focus laser	Y	2	0
201	13	12	Process Data		N	0	2
201	131	13	Receive reflected light	Receive laser	Y	1	0
201	14	14	Convert data		N	0	2
201	141	15	Convert reflected light to electrical energy	Convert laser to electrical power	Y	2	0
201	15	16	Amplify		N	0	1
201	151	17	Increase amplitude of waves		N	0	2
201	16	18	Output amplified sound		N	0	2
201	161	19	Transport sound	Output sound	P	1	0
201	162	20	Convert amplified waves to sound		N	0	3
201	17	21	Keep user safe		N	0	2
201	171	22	Block laser from user	Keep laser from user	P	2	0

				Functional Description Template			
User ID	Func ID	Func #	Orginal Functions	Functions	Correct	Matches	Lost Info
201	172	23	Keep spinning CD away from user	Keep disc from user	P	2	0
201	173	24	Insulate to avoid electric shock	Keep electrical power from user	P	1	0
201	18	25	Support the structure		N	0	2
201	181	26	Keep power source contained	Contain electrical power	Y	2	0
201	182	27	Fix positions of parts		N	0	2
202	0	1	Play CDs	Sound CD	Y	1	0
202	1	2	Load CD	Insert CD	Y	1	0
202	11	3	Open CD housing	Open Housing	Y	2	0
202	12	4	Position CD on spinning mechanism	Position CD on Spinning Mechanism	Y	4	0
202	2	5	Transport CD	Transport CD	Y	2	0
202	21	6	Portable housing	Deliver Housing	Y	1	0
202	22	7	Latch CD housing closed	Secure Latch to Housing	Y	2	0
202	3	8	Power Device	Power CD	Y	1	0
202	31	9	Switch ON	Activate Power Switch to Batteries	Y	1	0
202	32	10	Supply battery power	Deliver Current from Batteries	Y	1	0
202	4	11	Read CD	Read CD	Y	2	0
202	41	12	Spin CD	Spin CD	Y	2	0
202	42	13	Project laser eye to CD surface	Focus Laser Eye on CD	Y	3	0
202	5	14	Display statistics	Display Track Data	Y	1	0
202	51	15	Read track data	Read Track Data	Y	3	0
202	52	16	Print track data on LCD screen	Display Track Data on LCD Display	Y	4	0
202	6	17	Transmit Sound	Communicate CD	P	0	0
202	61	18	Interpret laser eye readings	Compute Track Data	Y	0	0
202	62	19	Convert to audio	Convert Track Data	Y	1	0
202	63	20	Adjust volume	Adjust Volume Knob	P	2	0
202	64	21	Connect to headphones	Link Headphones	Y	1	0
203	0	1	Play a music CD		N	0	2
203	1	2	Open cd payer		N	0	2
203	1a	3	Move latch to open lid	Move latch	Y	2	1
203	2	4	Insert cd		N	0	2
203	2a	5	Snap cd onto cd holder	Place cd onto cd holder	Y	3	0
203	3	6	Close cd player		N	0	2

				Functional Description Template			
User ID	Func ID	Func #	Orginal Functions	Functions	Correct	Matches	Lost Info
203	3a	7	Close lid such that latch engages to hold lid closed		N	0	4
203	4	8	Spin up cd		N	0	2
203	4a	9	Activate motor	Rotate motor	P	1	0
203	4b	10	Ensure motor spins to proper rpm	Determine Angular velocity of cd	Y	0	0
203	5	11	Align laser		N	0	2
203	5a	12	Move laser with screw drive	Move laser assembly with screw drive	Y	4	0
203	5b	13	Align laser with track on cd	Align laser assembly with music data	Y	2	0
203	6	14	Play music		N	0	2
203	6a	15	Read data from cd	Read music data from cd	Y	3	0
203	6b	16	Continuously move laser to stay aligned with track on cd	Maintain laser assembly aligned with music data	P	2	0
203	7	17	Stop cd		N	0	2
203	7a	18	Stop motor from spinning	Stop motor	Y	2	0
203	8	19	Open cd player	Open cd player lid	Y	3	0
203	8a	20	Move latch to open lid	Move latch	Y	2	1
203	9	21	Remove cd		N	0	2
203	9a	22	Snap cd off of cd holder	Remove cd from cd holder	Y	3	0
203	10	23	Close cd player		N	0	2
203	10a	24	Close lid such that latch engages to hold lid closed	Close cd player lid	Y	2	2
205	0	1	Play music	Play Music	Y	2	0
205	1	2	Accept CD	Accept CD	Y	2	0
205	1a	3	Open compartment	Open CD player	Y	1	0
205	1b	4	Insert CD	Insert CD	Y	2	0
205	1c	5	Close compartment	Close CD player	Y	1	0
205	2	6	Read CD	Read CD	Y	2	0
205	2a	7	Drive motor spins CD	Rotate CD using Drive motor	Y	3	0
205	2b	8	Focus laser onto CD	Focus Laser onto CD	Y	3	0
205	2c	9	Photodiode captures laser reflectance	Measure Reflectivity of CD	Y	1	1
205	3	10	Play Music	Play Music	Y	2	0

				Functional Description Template			
User ID	Func ID	Func #	Orginal Functions	Functions	Correct	Matches	Lost Info
205	3a	11	Convert photodiode signal to audio	Convert Reflectivity of CD	P	1	1
205	3b	12	Send output to headphones	Deliver Music to User	Y	0	0
205	4	13	Edit sound	Change Music	Y	0	0
205	4a	14	Skip tracks	Specify CD data	Y	0	0
205	4b	15	Increase volume	Increase Amplitude of Music	Y	1	0
205	4c	16	Pause music	Pause Music	Y	2	0
205	4d	17	Fast Forward music	Forward Music	Y	2	0
205	4e	18	Rewind music	Reverse Music	P	1	0
205	5	19	Eject CD	Eject CD	Y	2	0
205	5a	20	Press eject button		N	0	2
205	5b	21	Open compartment	Open CD player	Y	1	0
205	5c	22	Extract CD	Eject CD	Y	1	0
302	0	1	Play Music	Provide Sound Waves	Y	0	0
302	1	2	Load CD	Receive CD	Y	1	0
302	11	3	Allow for placement of CD	Manipulate Location of CD	P	1	0
302	12	4	Contain CD	Contain CD	Y	2	0
302	13	5	Protect CD from outside elements	Isolate CD from Dust	Y	1	0
302	14	6	Allow for removal of CD	Remove CD	Y	2	0
302	2	7	Read Data from CD	Retrieve Data from CD	Y	2	0
302	21	8	Rotate CD	Rotate CD	Y	2	0
302	22	9	Allow for track selection	Select Tracks on CD	Y	2	0
302	23	10	Gather optical data	Gather Up Data	Y	2	0
302	24	11	Convert optical data to analog electrical signals	Convert Data to Electrical Signal	Y	4	0
302	3	12	Output data	Output Data	Y	2	0
302	31	13	Send signal to speakers	Send Electrical Signal to Speakers	Y	3	0
302	32	14	Convert signal to magnetic fields	Convert Electrical Signal to Magnetic Waves	Y	3	0
302	33	15	Convert magnetic fields to acoustic waves	Convert Magnetic Waves to Sound Waves	Y	3	0
302	4	16	Provide power	Provide Power	Y	2	0
302	5	17	Allow user to turn entire device on/off	Change State of CD Player	P	0	0

				Functional Description Template			
User ID	**Func ID**	**Func #**	**Orginal Functions**	**Functions**	**Correct**	**Matches**	**Lost Info**
305	1	1	Plays audio CDs	Rotate CD	P	1	0
305	1.1	2	Get power	Get Power from Battery/Power source	Y	2	0
305	1.1.1	3	Put on the ear plugs/head phones	Put Head phone	Y	3	0
305	1.1.2	4	Connect power cable if necessary and turn on the power mode	Connect Battery/Power source	Y	2	2
305	1.2	5	Insert a CD	Position CD	Y	1	0
305	1.2.1	6	Open the lid to insert CD or just press the insertion button	Open CD insertion slot	Y	3	4
305	1.2.2	7	Place the CD on the slot	Place CD on CD insertion slot	Y	3	0
305	1.2.3	8	Close the lid or press the insertion done button	Close CD insertion slot	Y	2	2
305	1.3	9	Play a CD	Play CD	Y	2	0
305	1.3.1	10	Press the play button	Start Play button	Y	2	0
305	1.3.2	11	CD starts playing		N	0	2
305	1.3.3	12	Enjoy the music	Listen to Sound	Y	0	0
305	1.4	13	Pause/Stop playing a CD	Stop CD	Y	2	0
305	1.4.1	14	Press the pause/stop button	Stop Play button	P	2	0
305	1.4.2	15	CD stops playing		N	0	2
305	1.5	16	Remove the CD	Eject CD	Y	1	0
305	1.5.1	17	Open the lid or press eject button	Open CD insertion slot	Y	1	2
305	1.5.2	18	Take out the CD	Remove CD	Y	1	0
305	1.5.3	19	Close the lid or press ejection done button	Close CD insertion slot	Y	1	2
305	1.6	20	Turn off power	Turn off Power of Battery/Power source	Y	3	0
305	1.6.1	21	Press the power button once again to stop getting power anymore and disconnect power cables if required	Disconnect Battery/Power source	Y	2	4
305	1.6.2	22	Take off the ear plugs/head phones	Remove Head phone	Y	2	0
306	1	1	Play music from a CD	Play Music from CD	Y	3	0

				Functional Description Template			
User ID	**Func ID**	**Func #**	**Orginal Functions**	**Functions**	**Correct**	**Matches**	**Lost Info**
306	11	2	Provide mechanism for mounting and ejecting CD's	Position CD	Y	1	3
306	111	3	Open CD compartment	Open CD Player Body	Y	2	0
306	112	4	Mount/Remove CD	Put in CD	Y	1	0
306	113	5	Close CD compartment	Close CD Player Body	Y	2	0
306	12	6	Select track information	Select Track	Y	2	0
306	121	7	Select track	Select Track	Y	2	0
306	122	8	Spin CD at specific angular velocity	Spin CD	Y	2	1
306	13	9	Play CD	Play CD	Y	2	0
306	131	10	Read track data using CD track reader	Read Track using CD Track Reader	Y	5	0
306	132	11	Convert rotational energy into signal using data	Convert Rotational Energy to Signal	Y	4	1
306	133	12	Transport signal to headphones	Transport Signal to Head Phones	Y	4	0
306	134	13	Convert signal into sound energy using headphones	Convert Signal to Sound Energy	Y	4	1
306	14	14	Display track information	Display Track	Y	2	0
306	141	15	Read track data using CD track reader	Read Track	Y	2	1
306	142	16	Convert electrical energy from battery to light energy to display track data	Convert Electrical Energy to Data	Y	4	3
307	1	1	Output Sound	Sound SPEAKERS	N	1	1
307	11	2	Hold CD	Hold CD	Y	2	0
307	111	3	Orient CD in proper position	Align CD	Y	1	1
307	112	4	Prevent CD face from being scratched	Stabilize CD	P	1	1
307	12	5	Spin CD	Spin CD	Y	2	0
307	121	6	Spin at correct RPM	Control Rotation OF CD	Y	0	0
307	122	7	Hold CD for rotation	Stabilize Area OF CD	Y	1	1
307	123	8	Keep CD face planar		N	0	2
307	13	9	Read CD	Acquire Information FROM CD	P	1	0
307	131	10	Laser watts	Control Intensity OF LASER	Y	1	0
307	132	11	Move CD over laser	Spin CD	Y	1	1
307	14	12	Eject CD	Release CD	Y	1	0
307	141	13	Initiate ejection	Initiate CD TO HAND	P	1	0

				Functional Description Template			
User ID	**Func ID**	**Func #**	**Orginal Functions**	**Functions**	**Correct**	**Matches**	**Lost Info**
307	142	14	Prevent CD face from being scratched	Stabilize CD	P	1	1
307	15	15	Output Sound	Output Amplitude TO SPEAKERS	P	1	0
307	151	16	Adjust Volume	Adjust Amplitude OF SPEAKERS	P	1	0
307	152	17	Transmit to speakers	Transmit Frequency TO SPEAKERS	P	2	0
307	16	18	Portability	Transport CASE	Y	0	0
307	161	19	Weight	Minimize Mass OF CASE	N	0	0
307	162	20	Size	Minimize Volume OF CASE	N	0	0
307	163	21	Skip prevention	Stabilize CD	N	0	0

Appendix D7: Functional Description Template Function Classifications

User ID	Func ID	Func #	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	Property Type
101	1	1	Start	Play	Material	Solid				
101	1.1	2	Start	Operate	Artifact	Device	Energy	Electrical		
101	1.1.1	3	Move	Transfer	Energy	Electrical	Artifact	Device		
101	1.1.2	4	Maintain	Regulate	Energy	Electrical	Artifact	Device		
101	1.2	5	Detect	Read	Material	Solid	Artifact	Device		
101	1.2.1	6	Move	Move	Artifact	Device	Material	Solid		
101	1.2.2	7	Move	Send	Data	Binary	Artifact	Object		
101	1.3	8	Change	Convert	Data	Binary	Wave	Sound		
101	1.3.1	9	Acquire	Get	Data	Binary	Artifact	Object		
101	1.3.2	10	Change	Convert	Data	Binary				
101	1.3.3	11	Move	Send	Wave	Sound				
101	1.4	12	Maintain	Regulate	Wave	Sound				
101	1.4.1	13	Stop	Prevent	Wave	Sound				
101	1.4.2	14	Detect	Detect	Artifact	Object				
101	1.5	15	Provide	Allow	Living entity	Organism: Human				
101	1.5.1	16	Change	Convert	Artifact	Object	Energy	Electrical		
101	1.5.2	17	Move	Send	Energy	Electrical	Artifact	Object		
101	1.5.3	18	Move	Send	Wave	Sound	Wave	Sound		
102	0	1	Start	Play	Artifact	Object	Energy	Electrical		
102	1	2	Rotate	Spin	Artifact	Object				
102	11	3	Inject	Insert	Artifact	Object				
102	12	4	Secure	Secure	Artifact	Object				
102	13	5	Rotate	Spin	Artifact	Object				
102	2	6	Provide	Provide	Artifact	Device				
102	21	7	Contain	Store	Artifact	Device				
102	22	8	Detect	Sense	Artifact	Device				
102	23	9	Inject	Insert	Artifact	Device				
102	3	10	Change	Convert	Wave	Sound				
102	31	11	Detect	Receive	Artifact	Object				

User ID	Func ID	Func #	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	Property Type
102	32	12	Change	Convert	Wave	Sound				
102	4	13	Start	Play	Wave	Sound				
102	41	14	Increase	Amplify	Wave	Sound				
102	42	15	Move	Transfer	Wave	Sound	Artifact	Device		
102	43	16	Guide	Focus	Wave	Sound	Living entity	Organism: Human		
102	5	17	Start	Use	Energy	Electrical				
102	51	18								
102	52	19	Remove	Remove	Energy	Electrical				
102	6	20	Collect	Collect	Wave	Sound	Artifact	Object		
102	61	21	Guide	Focus	Artifact	Device				
102	62	22	Communicate	Communicate	Wave	Sound				
103	0	1	Start	Play	Wave	Sound				
103	1	2	Inject	Insert	Artifact	Object	Artifact	Device		
103	11	3	Move	Open	Artifact	Object				
103	12	4	Secure	Fix	Artifact	Object	Artifact	Device		
103	13	5	Move	Close	Artifact	Object				
103	2	6	Specify	Select	Artifact	Object				
103	21	7	Rotate	Spin	Artifact	Object				
103	22	8	Position	Place	Artifact	Device				
103	3	9	Detect	Read	Artifact	Object				
103	31	10	Guide	Focus	Artifact	Device	Artifact	Object		
103	32	11	Eject	Emit	Wave	Electromagnetic				
103	33	12	Change	Convert	Wave	Electromagnetic	Data	Binary		
103	34	13	Change	Convert	Data	Binary	Wave	Sound		
103	35	14	Move	Move	Artifact	Device	Artifact	Object		
103	36	15								
103	4	16	Eject	Emit	Wave	Sound				
103	41	17	Increase	Amplify	Wave	Sound				
103	42	18	Eject	Emit	Wave	Sound	Artifact	Device		

User ID	Func ID	Func #	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	Property Type
104	0	1	Change	Convert	Data	Audio	Energy	Electrical		
104	1	2	Contain	Keep	Artifact	Object				
104	11	3	Acquire	Accept	Artifact	Object				
104	12	4	Secure	Lock	Artifact	Object				
104	13	5	Eject	Eject	Artifact	Object				
104	2	6	Change	Convert	Data	Audio	Data	Binary		
104	21	7	Rotate	Spin	Artifact	Object				
104	22	8	Move	Translate	Artifact	Device				
104	23	9	Change	Convert	Data	Audio	Data	Binary		
104	3	10	Change	Convert	Data	Binary	Energy	Electrical		
104	31	11	Change	Convert	Data	Binary				
104	32	12	Contain	Cache	Data	Binary				
104	33	13	Change	Convert	Data	Binary	Energy	Electrical		
104	34	14	Increase	Amplify	Energy	Electrical				
104	4	15	Provide	Output	Data	Binary	Artifact	Device		
104	41	16	Measure	Check	Data	Binary				
104	42	17	Provide	Output	Data	Binary	Artifact	Device		
104	5	18	Acquire	Accept	Energy	Mechanical	Artifact	Device		
104	51	19								
104	52	20								
201	1	1	Create	Produce	Wave	Sound				
201	11	2	Rotate	Rotate	Artifact	Object				
201	111	3	Maintain	Hold	Artifact	Object				
201	112	4	Change	Convert	Energy	Electrical				
201	113	5	Maintain	Maintain	Artifact	Device			Frequency	Waves
201	12	6	Detect	Read	Artifact	Object				
201	121	7	Maintain	Steady	Energy	Electromagnetic				
201	122	8	Move	Translate	Energy	Electromagnetic				
201	123	9	Change	Convert	Energy	Electrical				

User ID	Func ID	Func #	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	Property Type
201	124	10	Move	Move	Energy	Electromagnetic				
201	125	11	Guide	Focus	Energy	Electromagnetic				
201	13	12								
201	131	13	Acquire	Receive	Energy	Electromagnetic				
201	14	14								
201	141	15	Change	Convert	Energy	Electromagnetic	Energy	Electrical		
201	15	16								
201	151	17								
201	16	18								
201	161	19	Provide	Output	Wave	Sound				
201	162	20								
201	17	21								
201	171	22	Maintain	Keep	Energy	Electromagnetic	Living entity	Organism: Human		
201	172	23	Maintain	Keep	Artifact	Object	Living entity	Organism: Human		
201	173	24	Maintain	Keep	Energy	Electrical	Living entity	Organism: Human		
201	18	25								
201	181	26	Contain	Contain	Energy	Electrical				
201	182	27								
202	0	1	Communicate	Sound	Artifact	Object				
202	1	2	Inject	Insert	Artifact	Object				
202	11	3	Move	Open	Artifact	Object				
202	12	4	Position	Position	Artifact	Object	Artifact	Object		
202	2	5	Move	Transport	Artifact	Object				
202	21	6	Move	Deliver	Artifact	Object				
202	22	7	Secure	Secure	Artifact	Object	Artifact	Object		

User ID	Func ID	Func #	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	Property Type
202	3	8	Start	Power	Artifact	Object				
202	31	9	Start	Activate	Artifact	Object	Artifact	Object		
202	32	10	Provide	Deliver	Artifact	Object			Current	Electromagnetic
202	4	11	Detect	Read	Artifact	Object				
202	41	12	Rotate	Spin	Artifact	Object				
202	42	13	Guide	Focus	Artifact	Object	Artifact	Object		
202	5	14	Communicate	Display	Data	Audio				
202	51	15	Detect	Read	Data	Audio				
202	52	16	Communicate	Display	Data	Audio	Artifact	Object		
202	6	17	Communicate	Communicate	Artifact	Object				
202	61	18	Measure	Compute	Data	Audio				
202	62	19	Change	Convert	Data	Audio				
202	63	20	Change	Adjust	Artifact	Object				
202	64	21	Connect	Link	Artifact	Device				
203	0	1								
203	1	2								
203	1a	3	Move	Move	Artifact	Object				
203	2	4								
203	2a	5	Position	Place	Artifact	Object	Artifact	Object		
203	3	6								
203	3a	7								
203	4	8								
203	4a	9	Rotate	Rotate	Artifact	Object				
203	4b	10	Measure	Determine	Artifact	Object			Angular velocity	Motion
203	5	11								
203	5a	12	Move	Move	Artifact	Object	Artifact	Object		
203	5b	13	Guide	Align	Artifact	Object	Data	Binary		
203	6	14								
203	6a	15	Detect	Read	Data	Binary	Artifact	Object		
203	6b	16	Maintain	Maintain	Artifact	Object	Data	Binary		

User ID	Func ID	Func #	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	Property Type
203	7	17								
203	7a	18	Stop	Stop	Artifact	Object				
203	8	19	Move	Open	Artifact	Object				
203	8a	20	Move	Move	Artifact	Object				
203	9	21								
203	9a	22	Remove	Remove	Artifact	Object	Artifact	Object		
203	10	23								
203	10a	24	Move	Close	Artifact	Object				
205	0	1	Start	Play	Energy	Acoustic				
205	1	2	Acquire	Accept	Material	Solid				
205	1a	3	Move	Open	Artifact	Device				
205	1b	4	Inject	Insert	Material	Solid				
205	1c	5	Move	Close	Artifact	Device				
205	2	6	Detect	Read	Material	Solid				
205	2a	7	Rotate	Rotate	Material	Solid	Artifact	Device		
205	2b	8	Guide	Focus	Wave	Electromagnetic	Material	Solid		
205	2c	9	Measure	Measure	Material	Solid			Reflectivity	Material
205	3	10	Start	Play	Energy	Acoustic				
205	3a	11	Change	Convert	Material	Solid			Reflectivity	Material
205	3b	12	Provide	Deliver	Energy	Acoustic	Living entity	Organism: Human		
205	4	13	Change	Change	Energy	Acoustic				
205	4a	14	Specify	Specify	Data	Binary				
205	4b	15	Increase	Increase	Energy	Acoustic			Amplitude	Waves
205	4c	16	Stop	Pause	Energy	Acoustic				
205	4d	17	Move	Forward	Energy	Acoustic				
205	4e	18	Change	Reverse	Energy	Acoustic				
205	5	19	Eject	Eject	Material	Solid				
205	5a	20								

User ID	Func ID	Func #	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	Property Type
205	5b	21	Move	Open	Artifact	Device				
205	5c	22	Eject	Eject	Material	Solid				
302	0	1	Provide	Provide	Wave	Sound				
302	1	2	Acquire	Receive	Artifact	Object				
302	11	3	Change	Manipulate	Artifact	Object			Location	Motion
302	12	4	Contain	Contain	Artifact	Object				
302	13	5	Separate	Isolate	Artifact	Object	Material	Solid		
302	14	6	Remove	Remove	Artifact	Object				
302	2	7	Acquire	Retrieve	Data	Binary	Artifact	Object		
302	21	8	Rotate	Rotate	Artifact	Object				
302	22	9	Specify	Select	Data	Audio	Artifact	Object		
302	23	10	Acquire	Gather Up	Data	Binary				
302	24	11	Change	Convert	Data	Binary	Energy	Electrical		
302	3	12	Provide	Output	Data	Binary				
302	31	13	Move	Send	Energy	Electrical	Artifact	Device		
302	32	14	Change	Convert	Energy	Electrical	Wave	Electromagnetic		
302	33	15	Change	Convert	Wave	Electromagnetic	Wave	Sound		
302	4	16	Provide	Provide	Energy	Electrical				
302	5	17	Change	Change	Artifact	Device			State	Electromagnetic
305	1	1	Rotate	Rotate	Artifact	Object				
305	1.1	2	Acquire	Get	Artifact	Object			Power	Mechanics
305	1.1.1	3	Position	Put	Artifact	Device				
305	1.1.2	4	Connect	Connect	Artifact	Object				
305	1.2	5	Position	Position	Artifact	Object				
305	1.2.1	6	Move	Open	Artifact	Object				
305	1.2.2	7	Position	Place	Artifact	Object	Artifact	Object		
305	1.2.3	8	Move	Close	Artifact	Object				
305	1.3	9	Start	Play	Artifact	Object				
305	1.3.1	10	Start	Start	Artifact	Object				

User ID	Func ID	Func #	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	Property Type
305	1.3.2	11								
305	1.3.3	12	Detect	Listen to	Energy	Acoustic				
305	1.4	13	Stop	Stop	Artifact	Object				
305	1.4.1	14	Stop	Stop	Artifact	Object				
305	1.4.2	15								
305	1.5	16	Eject	Eject	Artifact	Object				
305	1.5.1	17	Move	Open	Artifact	Object				
305	1.5.2	18	Remove	Remove	Artifact	Object				
305	1.5.3	19	Move	Close	Artifact	Object				
305	1.6	20	Stop	Turn off	Artifact	Object			Power	Mechanics
305	1.6.1	21	Separate	Disconnect	Artifact	Object				
305	1.6.2	22	Remove	Remove	Artifact	Device				
306	1	1	Start	Play	Data	Audio	Artifact	Object		
306	11	2	Position	Position	Artifact	Object				
306	111	3	Move	Open	Artifact	Object				
306	112	4	Inject	Put in	Artifact	Object				
306	113	5	Move	Close	Artifact	Object				
306	12	6	Specify	Select	Data	Binary				
306	121	7	Specify	Select	Data	Binary				
306	122	8	Rotate	Spin	Artifact	Object				
306	13	9	Start	Play	Artifact	Object				
306	131	10	Detect	Read	Data	Binary	Artifact	Device		
306	132	11	Change	Convert	Energy	Mechanical	Energy	Electrical		
306	133	12	Move	Transport	Energy	Electrical	Artifact	Device		
306	134	13	Change	Convert	Energy	Electrical	Energy	Acoustic		
306	14	14	Communicate	Display	Data	Binary				
306	141	15	Detect	Read	Data	Binary				
306	142	16	Change	Convert	Energy	Electrical	Data	Text		
307	1	1	Communicate	Sound	Artifact	Device				
307	11	2	Secure	Hold	Artifact	Object				
307	111	3	Position	Align	Artifact	Object				
307	112	4	Secure	Stabilize	Artifact	Object				

User ID	Func ID	Func #	Action	Synonym	Entity1Type1	Entity1Type2	Entity2Type1	Entity2Type2	Property	Property Type
307	12	5	Rotate	Spin	Artifact	Object				
307	121	6	Maintain	Control	Artifact	Object			Rotation	Motion
307	122	7	Secure	Stabilize	Artifact	Object			Area	Geometric
307	123	8								
307	13	9	Acquire	Acquire	Artifact	Object			Information	Material
307	131	10	Maintain	Control	Artifact	Device			Intensity	Mechanics
307	132	11	Rotate	Spin	Artifact	Object				
307	14	12	Eject	Release	Artifact	Object				
307	141	13	Start	Initiate	Artifact	Object	Living entity	Organism: Human		
307	142	14	Secure	Stabilize	Artifact	Object				
307	15	15	Eject	Output	Artifact	Device			Amplitude	Waves
307	151	16	Change	Adjust	Artifact	Device			Amplitude	Waves
307	152	17	Move	Transmit	Artifact	Device			Frequency	Waves
307	16	18	Move	Transport	Space	Space				
307	161	19	Decrease	Minimize	Space	Space			Mass	Mechanics
307	162	20	Decrease	Minimize	Space	Space			Volume	Geometric
307	163	21	Secure	Stabilize	Artifact	Object				

Appendix D8: Evaluations

User 101

1. Functional Description Template was a little bit easier.

2. Functional Description Template was much more accurate.

3. The Functional Description Template is approaching too many terms to be easily navigable to find the desired term

User 102

1. Functional Description Template was much easier.

2. Functional Description Template was a little bit more accurate.

3. I thought both methods were very difficult and time consuming to use. Not knowing the pool of words that we get to choose from makes searching very exhausting. It took a very long time (over 1.5 hrs) to enter in the small amount of information for a portable CD player in both databases (although the template version was slightly quicker and more user friendly than the other). However, I was frustrated and exhausted and ready to give up half way through the first method. By the time I got to the 2nd method I was not very interested in doing it all over again.

   Suggestions/Comments:
   Simplify the interface. There is too much to choose from. It makes searching for the exact word very time consuming. Even if the word that you are looking for exists, it is difficult to find the correct path to the word you are looking for.

   Word association (for more complicated words) is not the same for any two people. I think instead of the user being forced to conform their words to the existing words in the database, the software should search and suggest several words close to the meaning.

   The user should be able to type in their functions and the computer should translate them into its own language. Forcing the user to do the translation with an unfamiliar program is difficult.

   I had trouble finding the exact words I was looking for in the basis version so I usually just compromised and picked something that I thought was close but usually felt that some of the meaning was lost by doing so.

   Develop a template to lay out the way the FRs are written so that each user will have to follow the same format.

Hierarchal order for the FRs would be nice. Allow the user to indent and reorder and insert new FRs where they choose. Right now the only option is to add or remove, no edit.

User 103

1. Functional Description Template was much easier.

2. Functional Description Template was much more accurate.

3. Functional Description Template gives much choice both for entities and for functions. The only problem is that it takes some time to find the right function or entity in some cases. In this case the option *other being added to each category is very useful.

User 104

1. Functional Basis was a little bit easier.

2. Functional Description Template was much more accurate.

3. First of all, a typo:
   In Functional Basis method:
   The Function Description for Channel -> Transfer
   Transfer: To shift, or convey, a flow (material, energy, signal) from one place to another.

   Secondly, I had problem with the webpage for Functional Description Template when using Netscape 7.2. But everything works just fine after I switched to IE. The problem with Netscape was that, the Property Description wouldn't change appropriately when I selected different properties. It stays at "Chemical properties".

   Thirdly, one thing in Functional Description Template that confused me is that, the sub properties of Motion seem to be overlapping. For example, there are Rotation and Velocity, but at the same time Angular Velocity is also an option.

User 201

1. Functional Description Template was a little bit easier.

2. Functional Description Template was much more accurate.

3. FDT was overall easier to use than the FB, but the FDT action list was hard to use because it was not in alphabetical order. Sometimes I had not defined all of the

entities I need to describe a particular function, so I had to go back and add more entities. Many of the properties I had chosen for particular entities were not used, so it seemed like a waste of time to enter many properties and then not use them later. However, this information may be useful later on in the design stage. Both methods took about the same amount of time.

User 202

1. Functional Description Template was much easier.

2. Functional Description Template was a little bit more accurate.

3. If I had taken more time and developed more entities originally, the template method would have been even better.

User 203

1. Functional Description Template was much easier.

2. Functional Description Template was much more accurate.

3. I had a hard time figuring out where to find things in the Basis method.

User 205

1. Functional Description Template was much easier.

2. Functional Description Template was much more accurate.

3. Template method is far superior to basis method. The only time I had trouble with the template was when a part of my decomposition was vague or poorly worded.

User 302

1. Functional Description Template was a little bit easier.

2. Functional Description Template was a little bit more accurate.

3. I thought Functional Description was a bit easier, but it was still difficult to (or unable to) make certain statements such as “allow user to (verb)”. It also seemed that more options were needed at times in the record functions segment to allow the user to make statements like using states and multiple entities like “convert state of data from electrical to acoustic.”

In addition, some of the words seem redundant in functional description. It is easier for the user to find his/her exact phrase, but eliminating direct synonyms wouldn't be much of a problem. I was often tempted to select the first word I saw that was a synonym of the word on my page rather than scan down to find my exact word even though it was there.

User 305

1. Functional Description Template was much easier.

2. Functional Description Template was much more accurate.

3. The description was far superior to the basis method; in fact I could not record most of my functions using the latter method. However, the interface for the description template needs to be improved. For example, provision must be kept to edit a function/entity rather than having to remove it and add it altogether. Moreover, in case of the basic level verbs, they are not arranged alphabetically which makes searching for the appropriate word irritating.

User 306

1. Functional Description Template was much easier.

2. Functional Description Template was much more accurate.

3. Functional Description Template was much more descriptive and accurate. I could locate the functions easily as most of the functions that I used in my functional decomposition were available. In case of Functional Basis, I spent time in deciding which functions are the closest to my function.

User 307

1. Functional Basis was a little bit easier.

2. Functional Description Template was much more accurate.

3. I tried to specify aspect of the laser in the Template version but there was no options that listed optical energy. The template gave many more options but it was difficult to differentiate between some of them. It seemed less organized. If the goal is to design a program so that multiple people will provide close to the same decomposition of a part then I find it hard to believe the template will provide that. Although it was slightly harder to fit some functions into the functional basis program, it felt more universal.

References

[Alts84] G. Altshuller. *Creativity as an Exact Science*, Gordon and Branch Publishers, Luxembourg, 1984.

[Alts98] G. Altshuller and L. Shulyak. *40 Principles: TRIZ Keys to Technical Innovation*, Technical Innovation Center, Inc., Worcester, MA, 1998.

[Ande99] J.M. Anderson and P.A. Kerrebrock The Vorticity Control Unmanned Undersea Vehicle (VCUUV): Performance Results. *11th International Symposium on Unmanned Untethered Submersible Technology*, Draper Report No. P-3747, Durham, NH, August, 1999.

[Autu00] K. Autumn. Adhesive Mechanisms Mini-Presentation. Autumn Lab - Climbing, http://www.lclark.edu/~autumn/climbing/climb.html, 2000.

[Ayer02] J. Ayers, J.L. Davis, and A. Rudolph, eds., Neurotechnology for Biomimetic Robots. Bradford Books, 2002.

[Ball01] P. Ball. *Life's Lessons in Design*. *Nature*, Vol 409, 2001.

[Beny02] J.M. Benyus. *Biomimicry: Innovation Inspired by Nature*. Harper Collins Publishers Inc, New York, NY, 2002.

[Boga02] O.A. Bogatyreva, A.K. Pahl, and J.F.V. Vincent. Enriching TRIZ with Biology: The Biological Effects database and implications for Teleology and Epistemology. *Proceedings of the 2002 Etria World Conference*, p.3-1-307, Strasbourg, November, 2002.

[Boga03] O.A. Bogatyreva, A.K. Pahl, A. Bowyer, and J.F.V. Vincent. Data gathering for putting biology in TRIZ. *Proceedings of TRIZcon 2003*, 18-1-18-7.

[Chiu04] I. Chiu and L.H. Shu. Natural Language Analysis for Biomimetic Design. *Proceedings of the 2004 ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Paper No. DETC2004-57250, Salt Lake City, UT, September, 2004.

[Clar01] J.E. Clark, J.G. Cham, S.A. Bailey, E.M. Froehlich, P.K. Nahata, R.J. Full, and M.R. Cutkosky. Biomimetic Design and Fabrication of a Hexapedal Running Robot. *IEEE International Conference on Robotics and Automation*, 2001.

[Cohe01] Y. Bar-Cohen. *Electroactive Polymer (EAP) Actuators as Artificial Muscles*. SPIE Press, Bellingham, 2001.

[Cohe03] Y. Bar-Cohen and C. Breazeal. Biologically Inspired Intelligent Robotics. Proceedings of the SPIE Smart Structures Conference, Paper 5051-02, San Diego, CA, 2003.

[Cohe98] Y. Bar-Cohen, T. Xue, M. Shahinpoor, J.O. Simpson, and J. Smith. Flexible, Low-mass Robotic Arm Actuated by EAP. *Proceedings of the SPIE International Smart Materials & Structures Conference*, SPIE Paper No. 3329-07, San Diego, CA, March, 1998.

[Ekst05] J. Ekstrom. "Velcro." Online image. SEM Images. May 2005. <http://science.exeter.edu/jekstrom/SEM/SEM.html>.

[Elli99] C.P. Ellington. The Novel Aerodynamics of Insect Flight: Applications to Micro-Air Vehicles. Journal of Experimental Biology, Vol 202, pp. 3439–3448, 1999.

[Fan02] Z. Fan, J. Chen, J. Zou, D. Bullen, C. Lui, and F. Delcomyn. Design and Fabrication of Artificial Lateral Line Flow Sensors. Journal of Micromechanics and Microengineering, Vol 12, pp 655-661, 2002.

[Geim03] A.K. Geim, S.V. Dubonos, I.V. Grigorieva, K.S. Novoselov, A.A. Zhukov and S.Yu. Shapoval. Microfabricated Adhesive Mimicking Gecko Foot-Hair. Nature Materials, 2003, Vol 2, pp 461-463.

[Hirt02] J. Hirtz, R.B. Stone, D.A. McAdams, S. Szykman, and K. Wood. A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts. *Research in Engineering Design*, 2002, Vol 13, No 2, 2002, pp 65-82.

[Kapl98] D.L. Kaplan. Mollusc Shell Structures: Novel Design Strategies for Synthetic Materials. *Current Opinion in Solid State Materials Science*, Vol 3, No 3, 1998.

[Korn95] R. Kornbluh, R. Pelrine and J. Joseph. Elastomeric Dielectric Artificial Muscle Actuators for Small Robots. *Proceeding of the 3rd IASTED International Conference*, Cancun, Mexico, June, 1995.

[Kuc97] R. Kuc. Biomimetic Sonar Locates and Recognizes Objects. IEEE Journal of Oceanic Engineering, Vol 22, No 4, 1997.

[Mak04] T.W. Mak and L.H. Shu. Use of Biological Phenomena in Design by Analogy. *Proceedings of the 2004 ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Paper No. DETC2004-57303, Salt Lake City, UT, September, 2004.

[Mara05] Marathon Seafood. "Yellowfin Tuna." 01 Jan. 2005. Online image. Marathon Seafood. May 2005. <http://marathonseafood.com/store/images/yellowfin_in_water_200.jpg>.

[Matt98] C. Mattheck. *Design in Nature: Learning from Trees*. Springer-Verlag, 1998.

[Matt03] G. Matthew. "Lesser burdock." 13 Aug. 2003. Online image. Wild Flowers and Plants. May 2005. <http://www.gpmatthews.nildram.co.uk/microscopes/wild_plants.html>.

[McKi02] J. McKittrick, J. Aizenberg, C. Orme, and P. Vekilov. Biological and Biomimetic Materials: Properties to Function. *Materials Research Society*, 2002.

[McRo99] A. McRobb. "Giant Water lily Victoria amazonica." 1999. Online image. Photo London. May 2005. <http://www.photolondon.org.uk/assoc_pages/kew/kewpics2.htm>.

[Mill03] G.A. Miller. WordNet 2.0. http://wordnet.princeton.edu, Princeton University, 2003.

[Pick00] J.P. Pickett et al., eds., *The American Heritage® Dictionary of the English Language*, 4th ed. Boston: Houghton Mifflin, 2000.

[Publ04] Public Affairs Office. "REMUS." 10 June 2004. Online image. Office of Naval Research. May 2005. <http://www.onr.navy.mil/media/view_gallerysingle_display.asp?ID=103>.

[Sari95] M. Sarikaya and I.A. Aksay. *Biomimetics: Design and Processing of Materials*. AIP Press, 1995.

[Sell98] A. Sellinger, P.M. Weiss, A. Nguyen, Y. Lu, R.A. Assink, W. Gong, and J. Brinker. Continuous Self-Assembly of Orgain-Inorganic Nanocomposite Coatings that Mimic Nacre. *Nature*, Vol 394, July, 1998.

[Shah94] M. Shahinpoor. Continuum Electromechanics of Ionic Polymeric Gels as Artificial Muscles for Robotic Applications. *Smart Materials and Structures*, Vol 3, pp. 367-372, 1994.

[Skor02] A. Skordos, P.H. Chan, J.F.V. Vincent, and G. Jeronimidis. A Novel Strain Sensor Based on the Campaniform Sensillum of Insects. *Philosophical Transactions of the Royal Society London A*, Vol 360, pp 239 – 253, 2002.

[Toko00] K. Toko. *Biomimetic Sensor Technology*. Cambridge University Press, 2000.

[Vinc00] J.F.V. Vincent and D.L. Mann. TRIZ in biology teaching. *TRIZ Journal*, September, 2000.

[Vinc02] J.F.V. Vincent and D.L. Mann. Systematic Technology Transfer from Biology to Engineering. *Philosophical Transactions of the Royal Society: Physical Sciences*, 2002, Vol 360, pp 159-173.

[Voge00] S. Vogel. *Cats' Paws and Catapults: Mechanical Worlds of Nature and People*. W.W. Norton and Company Inc., New York, NY, 2000.

[Voge03] S. Vogel. *Comparative Biomechanics: Life's Physical World*. Princeton University Press, Princeton, NJ, 2003.

[Wang94] Wang Yu-Qing, Wang Zuo-Ming, Zheng Jiu-Hong. Biomimetic Design of Interfaces for Metal Matrix Composites. *Biomimetics*, Vol 2, No 4, 1994.

[Wein99] E.F. Weinel. The Crystal Palace, London, England (1851) Joseph Paxton. History of the Built Environment II, <http://arch.ou.edu/arch/2423/Chapter%2023/slide3.htm>, 1999.