

A FUNCTION-BASED COMPONENT ONTOLOGY FOR SYSTEMS DESIGN

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ABSTRACT

A methodology for the systematic placement of components into a hierarchical ontology is proposed. Cues taken from the Linnaean classification system for living organisms were used to generate a hierarchical ontology for organizing component terms and to create a robust procedure for adding new component terms to an existing component naming scheme. The objective of this research is to begin constructing a hierarchical ontology that is analogous to the Linnaean classification system with specific rules that rigorously guide component placement within the framework. The primary motivation for this research is to develop an ontology of distinct components terms that supports computational strategies for automated design synthesis, general design knowledge storage and reuse, efficient communication of design information, and standardization for digital component cataloging and searching.

Keywords: electro-mechanical component classification, ports, functional basis of design, conceptual design, design reuse, device ontology

1 INTRODUCTION

Components are the fundamental artifacts from which physical devices are built. In the early stages of design, a designer must take a set of specifications and constraints and translate these design requirements into a set of compatible components that work together to solve a desired task. As an electromechanical design evolves from a loose conceptual sketch to a fully realized product design, designers make decisions regarding specific component geometry and performance. While formal component representations exist during the detailed stages of product development, electromechanical components lack similar representations that support the conceptual phase of design, leaving a designer to rely on personal experience or potentially time consuming search methods to identify an initial broad selection of distinct conceptual component configurations for a design. In addition, less experienced designers may find it difficult to produce a broad array of distinctly different potential solutions, and instead may generate several similar alternatives that may contain one or more components that are merely variations on a theme within the realm of his or her personal experience. In the early stages of design, specific details of component geometry and performance are less important than the ability to represent component knowledge at a higher level of abstraction [1]. The *functionality* of components provides a natural framework upon which such abstractions can be built. Previous work sought to develop and later refine a component naming convention for abstract functionally relevant component classes for first mechanical and later electromechanical components [2, 3]. The research presented here seeks to create a *hierarchical ontology* into which both new and existing component terms may be classified. It is hoped that this hierarchy, inspired by the animal classification system begun by Carolus Linnaeus, will help ensure that the goal of complete and exclusive inclusion of all components into the ontology will be maintained as new terms are added.

1.1 Motivation

Implementation of a Computational Theory for Design Synthesis: Many researchers have explored automated design tools to improve design synthesis activities [4-15]. Components typically

constitute the fundamental building blocks of these activities. Within the variety of computer aided design research, various methodologies and tools have been developed which require a rich library of components, however, there is no agreed upon standard component library. As a result of this, libraries of components are independently developed in an application specific manner. Creation of a structured framework for the classification of new and existing components will reconcile previous efforts into a single electromechanical component library that can be leveraged by a number of design automation methods.

Design Knowledge Reuse: Over the past few decades, systematic approaches to conceptual design have emerged [16-21]. These design methods begin by formulating the product function as a set of low level sub-functions, solutions to which are then synthesized together to arrive at a final design. The core of the computational synthesis methods [4-6] built upon this function-based framework is the mapping of sub-functions to components. This allows designers to generate concept variants from a generic functional description of the product being designed. Each of these computational methods requires a knowledge base of “reconfigurable” standardized component objects that can be archived, searched and reused. A defined ontology facilitates the organization of such a knowledge base so that various computational design tools can leverage existing design knowledge.

Communication of Design Knowledge: The use of natural language often leads to ambiguity in representing component design knowledge. Arbitrary and redundant component naming results in different interpretations among designers for similar concepts, hindering effective communication of design knowledge. By associating fundamental component concepts with uniquely defined component classes and by providing a structure for defining each term, improvements in uniformity and consistency in the representation of components and communication of design information for industry and design education are possible.

Standardization for Digital Component Cataloging: Solutions to conceptual design problems are usually represented as a configuration of components and interactions between them [6, 22]. The transformation from these configurations to fully embodied design solutions requires the specification of a system of electromechanical components that meet the overall design requirements. Given the breadth of suppliers and production methods that exist today, most engineered artifacts are a mix of both custom-made parts and OEM (original equipment manufacturer) parts. As a result, the OEM suppliers compete by striving to improve their components quality and variety. It is particularly important for them to catalogue their solutions such that they can be efficiently retrieved and incorporated into the design process. Technologies involving electronic representations of standard components and resulting digital databases are becoming more prominent in engineering design [23-25]. Contributing to these efforts, it is hoped that our ontology provides a useful classification scheme for vendors selling a variety of OEM components.

Motivated by these factors, we provide a starting point for the creation of a component ontology that is accessible to all design engineers. In the following sections, we will discuss other approaches to cataloging components, the use of ontologies in engineering design and computational synthesis, and a discussion of the biological parallels between classifying animals and classifying components (Section 2: Background). That is followed by a description of the method we used to create the proposed hierarchical framework and classify existing and new component naming terms within it, (Section 3: The Classification Hierarchy. Finally, we conclude with discussions (Section 4: Discussion and future work (Section 5: Future Work).

2 BACKGROUND

The motivation for developing a component ontology for systems design is analogous to that of the museum curator who archives artifacts from the universe around us as a repository of knowledge about those artifacts. Research in the field of artificial intelligence (AI) known as knowledge capture and representation is closely related to the work reported here. In general, ontology is a philosophical theory about the nature of existence, but AI researchers have adapted the term to describe “a shared and common understanding of some domain that can be communicated between people and application systems” [26]. Neches et al [27] claim: “An ontology defines the basic terms and relations comprising the vocabulary of a topic area.”

2.1 Artifact Classification

In this paper we take the view of an ontology as a construct for the classification of knowledge:

“An ontology may take a variety of forms, but necessarily it will include a vocabulary of terms, and some specification of their meaning. This includes definitions and an indication of how concepts are inter-related which collectively impose a structure on the domain and constrain the possible interpretations of terms.”[28]

A rich source for information about artifact classification is found in the ontologies used by museums. Because museums are in the business of collecting, cataloging, and classifying the artifacts of human endeavor, their curators have spent considerable energy in devising systematic means of cataloging their collections. One of the tools employed in this classification is a lexicon. The most commonly used lexicon is the one developed by Chenhall [29], who stated:

“The lexicon ... is based on the assumption that every man-made object was originally created to fulfill some function or purpose and, further, that original function is the only common denominator that is present in all of the artifacts of man, however simple or complex.”

In Chenhall’s view, the known (or assumed) function of an object represents the highest level of organizing principle upon which human-made artifacts can be classified and named. A logical system for naming objects consists of a ontology, or hierarchical ordering, based on three levels of relationships: (1) a controlled list of major categories; (2) a controlled vocabulary of classification terms; and (3) an open vocabulary of object names. Each of these levels is based on the function of the object:

- Major categories are a very limited set of easily remembered functional classes.
- Classification terms are carefully defined subdivisions of the major categories.
- Object names are the words used to identify individual artifacts.

The AI community takes a similar approach to component classification by using the function and form of a component as fundamental elements in its classification. The inclusion of function is a consistent theme in both the practical approach of Chenhall and the virtual approach of the AI community. The presence of component function in component naming is an important linkage between the theory of knowledge capture and representation and the theory of design. An understanding of function is integral to the design process [17, 21]; hence, a natural relationship between components and function must exist.

Another approach to classification comes from the Linnaean system of classifying species used in biology [30]. Carolus Linnaeus began the classification of living species during the early 1700s. Originally organizing plants by their reproductive structures, Linnaeus laid the foundations for the modern organism classification, which later led to striking observations and evolutionary theories about the similarities between functional forms found between species in the natural world. In the Linnaean system, the two classes are the genus class and the species name; these are equivalent to the classification and object name within the Chenhall system. In Chenhall’s lexicon, the classifications are defined very clearly, while the object names are left open ended. This approach allows those interested in the lexicon to add to the collected knowledge contained therein. When used properly, a classification and an object name from Chenhall’s lexicon results in a name that is unique in all of humankind’s creations.

One difficulty in developing an ontology for components is classification consistency. For example, does a long slender two-force member describe a link, a beam, or a shaft? Stahovich, et al. [31] claim that the fundamental ontology for mechanical devices should be based on object behavior not structure. Paredis, et al. [32] suggest that a complete description of a component requires the addition of form to the classification, where form specifies a particular instantiation of a component, e.g., a part number for a motor. Both approaches imply that behavior is a key element in classifying mechanical components. Does this clear up the issue of the long slender two force member? The behavior of this component is describable using the mathematical representation of the states of a device [17]. Modeling using the state representation of the component leads to an input/output relationship. Input/output relationships at a more abstract level are, by definition, the function of a component, device, or system. “A function of a product is a statement of a clear, reproducible relationship between the available input and the desired output of a product, independent of any particular form [21].” In the case of the long slender two force member, the input/output relationship is

to transmit force, where transmit force is a function taken from the functional basis of Hirtz et al [33]. Hence, it is proposed that the function of a component is the fundamental ontology for components.

In order to understand function as a basis for an ontology for components, it is necessary to discuss an ontology for functions. One such widely accepted ontology for functions is known simply as the Functional Basis.

2.2 Functional Basis

The Functional Basis is a set of function and flow terms that combine to form a sub-function description (in verb-object format.) Shown in Figure 1, the hierarchically arranged Basis terms, which are intended to span the entire electro-mechanical design space without repetition, are utilized during the generation of a black box model and functional model in order to encapsulate the actual or desired functionality of a product [33]. In this approach, the designer follows a rigorous set of steps to define a new or redesigned product's functionality prior to exploring specific solutions for the design problem [34].

		Primary Class	Secondary Class			Primary Class	Secondary Class
Functional Basis Reconciled Function Set	Branch		Separate	Functional Basis Reconciled Flow Set	Material		Human
			Distribute				Gas
	Channel		Import				Liquid
			Export				Solid
			Transfer				Plasma
			Guide				Mixture
	Connect		Couple		Signal		Status
			Mix				Control
	Control Magnitude		Actuate		Energy		Human
			Regulate				Acoustic
			Change				Chemical
			Stop				Electrical
	Convert		Convert				Electromagnetic
			Store				Hydraulic
	Provision		Supply				Magnetic
			Sense				Mechanical
Signal		Indicate		Pneumatic			
		Process		Radioactive/Nuclear			
Support		Stabilize		Thermal			
		Secure					
		Position					

Figure 1. Function and flow classes under the Functional Basis [33].

The black box model is constructed based on the overall product function and includes the various energy, material, and signal flows involved in the global functioning of the product. A detailed functional model is then derived from sub-functions that operate on the flows in the black box model. Repeatability, ease in storing and sharing design information, and increased scope in the search for solutions are some of the advantages the resulting functional models exhibit [34, 35].

Functional models reveal functional and flow dependencies and are used to capture design knowledge from existing products. Over the course of several years, A web-based repository of design knowledge has been developed and refined at the University of Missouri–Rolla and in collaboration with the University of Texas at Austin, Pennsylvania State University, Bucknell University, and Virginia Polytechnic Institute and State University [36, 37]. This repository, which includes descriptive product information such as functionality, component physical parameters, manufacturing processes, failure modes, and component connectivity, (see Figure 2), now contains detailed design knowledge on over 100 consumer products and the components that comprise them. The knowledge contained in the repository is steadily expanding and benefits from a broad base of consumer products. Design generation tools like function-component matrices (FCMs) and design structure matrices (DSMs) can be readily generated from single or multiple products and used in a variety of ways to enhance the design process [36, 37].

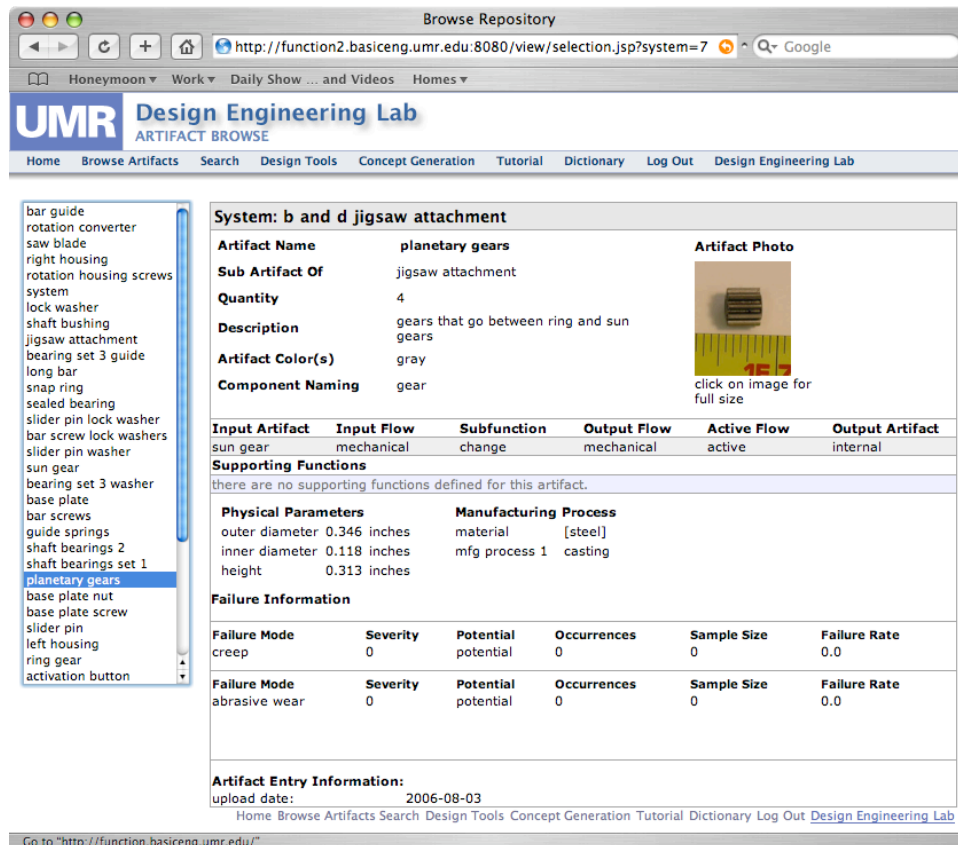


Figure 2. The UMR Design Repository web interface. Entry into the repository may be requested at <http://function.basiceng.umn.edu/repository>.

2.3 Observations

In this work, we find common ground between our goal for a basis set of component names in systems design and Chenhall's lexicon for classifying human-made artifacts. Because most components used in systems design are indeed human-made artifacts, they should be describable in the lexicon of Chenhall. Unfortunately, the lexicon does not include all possible artifact names, in fact "Artifacts originally created to be a physical part of some other object have, in most cases, been excluded from the lexicon" [29]. In terms of design, "artifacts originally created to be a physical part of some other object..." describe components.

Similarly, electro-mechanical devices share characteristics with living organisms that make the creation of a classification system analogous to the Linnaean classification, like having distinct observable form and function traits, varied levels of complexity, and a potential for partial overlap with traits from distinctly different components.

Since components cannot be adequately described in either Chenhall's lexicon or the Linnaean classification, we propose this function-based component ontology for systems design in order to establish a vocabulary of terms and a set of specifications for their inter-relationship. Therefore, similar to the way the Linnaean classification system has spawned an international code to ensure uniqueness and distinctness in naming biological terms, it is anticipated that the naming of new component terms under a component ontology should employ similar procedural guidelines

3 THE CLASSIFICATION HIERARCHY

Although not completely analogous, systems and their components share many traits with animals that make classification challenging. Originally, animal classifications were primarily based on visual observations of morphological similarity. More recently, biologists have used molecular and biochemical data in addition to morphological data to identify evolutionary links and classify animals under what is thought to be a more accurate binary tree structure known as cladistics [38]. Components are not evolutionary in the same sense that animals evolve from what is commonly thought to be a series of branching points, and the goal of classification in this research is focused

more on the practical use of the proposed hierarchical ontology. For this reason, we have chosen to initially begin with a function-based framework for the component classification hierarchy. The hierarchical framework was initially established from the notion that device function is an integral and critical characteristic of a component from the perspective of concept selection during the design process [17, 21]. As a starting point, the list of primary and secondary level function terms from the Functional Basis [33], shown in Figure 1, were used to designate the primary and secondary levels of the component framework.

3.1 Establishing the Hierarchy

In order to begin placing existing terms [3] into the framework, the functional traits of each device term needed to be established, where a device (component) is defined as having “input and output ports through which it is connected to another device [component]” [39]. The functional traits of each component term were determined by analyzing the individual components housed within the repository of product information and categorized under that component term. The black box functionality for each component term was defined by identifying the most commonly occurring sub-function (function-flow combination) assigned to each of the components classified under that term in the repository.

3.2 Placing Existing Component Terms into the Hierarchy

Function templates for each component term (see Figure 3) were generated to show the functions assigned to components within a given classification. In nearly every case, a component term would have a single function that was common among all components classified under that term. Exceptions included components that had errors resulting from entering the data into the repository (e.g. no conceptual functions were assigned to an electric motor) and components that are classified as *Provisioners* where the functions *Store* and *Supply* were nearly always both included as conceptual functions. The functional information was then used to locate the appropriate placement for the component term within the hierarchical framework.

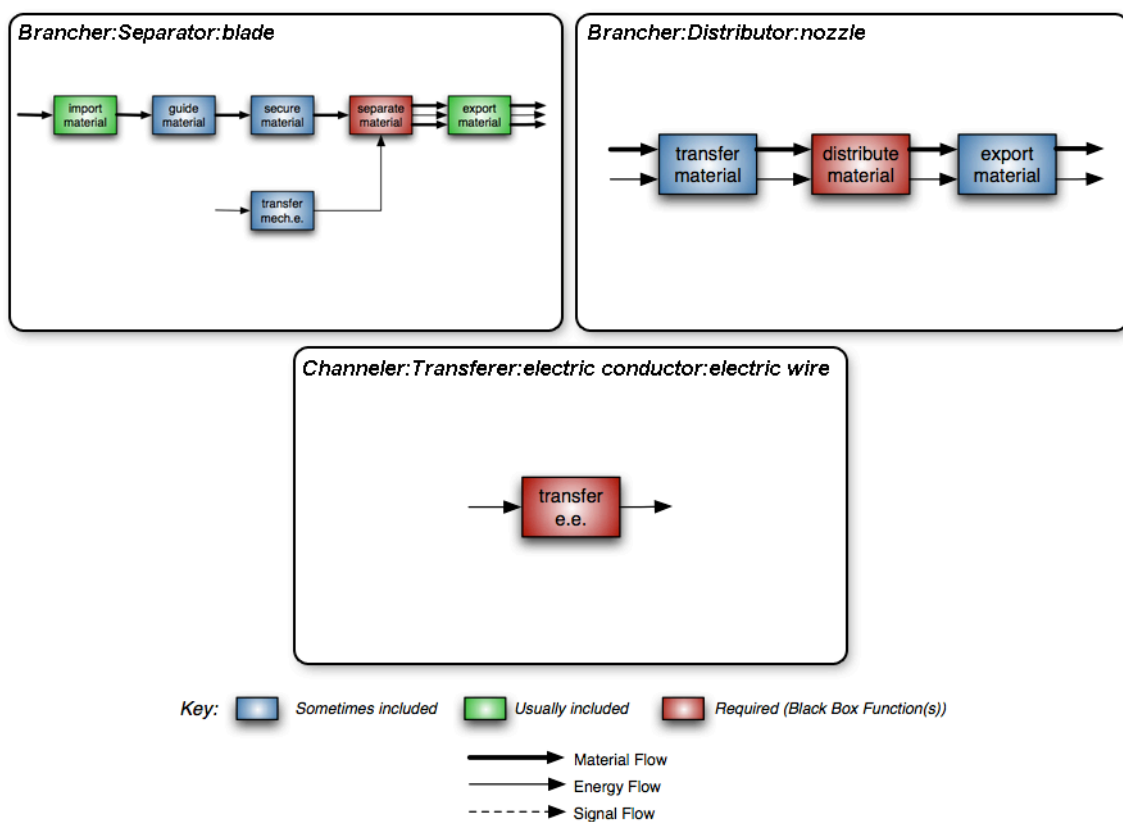


Figure 3. Function templates were used to help establish the functional characteristics of each component term. The templates were constructed using function and flow information entered into the web-based repository described in Section 2.

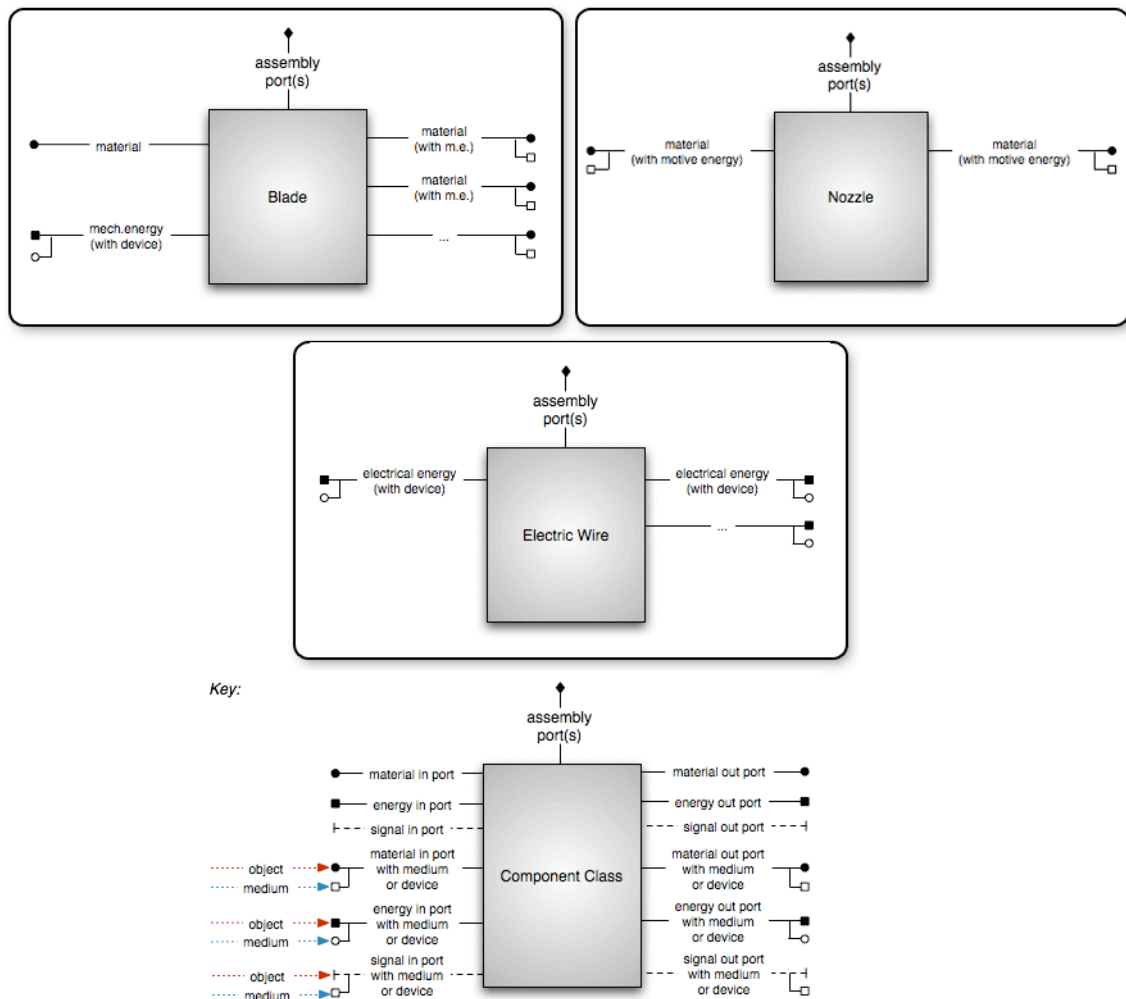


Figure 4. Port templates were also used to help establish the functional characteristics of each component term and to help create distinct definitions for each. Ports are indicated by lines into and out of the component box. Circles represent material flow ports, squares represent energy flow ports, and dashed lines with a vertical terminus represent signal flows. Components classes with members exhibiting variable numbers of repeating object ports are indicated by an output flow with ellipses (...), as shown for the electric wire.

In addition to function templates, templates that describe the major flows through a component were also established for each component term (Figure 4). In creating the port templates, the following port definitions were utilized:

Object port: A device port through which a flow (material, energy, or signal) enters and then travels through the device from the input port to the output port and is processed by the device [33, 39].

Medium port: A device port through which a flow (material, energy, or signal) enters and then travels through the device from the input port to the output port while holding an object and enabling it to flow through the device (e.g. water can act as a medium carrying hydraulic energy as an object through a device) [33, 39].

Assembly port: A device port that acts only as a mating surface to support the weight or stabilize the position of the device.

Flow information contained in the repository was used to identify all ports of a particular component. This information was then generalized to create a standard template for the component term group. For this research, port templates only include the object and medium flows that are directly relevant to the function the component performs (e.g. the *material* separated by a *blade* and the *mechanical energy*

used during the separation); waste flows, undesired flows, and reaction flows were not included (e.g. any *thermal* or *acoustic energy* that may result from a *blade* interacting with a *material* it is separating). Additionally, since they are not used at this point to help classify a component term, assembly connections were generalized into a single assembly port in each component template. Component term definitions within the hierarchical ontology were standardized using flow information from the port templates in addition to common morphological characteristics of the components within a single group (see Table 1 for an excerpt).

Table 1. An excerpt of component terms and definitions organized using the proposed hierarchical ontology.

Primary Component Classification	Secondary Component Classification	Component Term	Component Subset	Synonyms	Definition	
Branchers	Separators	...				
	Distributors	...				
Channelers	Importers/Exporters	...				
	Transferors	Carousel				A device used to move material in a continuous circular path.
		Conveyor				A device used to move material in a linear path.
		Electric Conductor		lead		A device used to transmit electrical energy from one component to another.
		Electric Wire				An electric conductor in the form of a thin, flexible thread or rod.
		Electric Plate				An electric conductor in the form of a thin, flat sheet or strip.
		Electric Socket				A device in the form of a receptacle that transmits electrical energy via a detachable connection with an electric plug.
		Electric Plug				A device in the form of a plug that transmits electrical energy via a detachable connection with an electric socket.
		Belt		strap, girdle, band, restraint		A device shaped as an endless loop of flexible material between two rotating shafts or pulleys used to transmit mechanical energy.
		...				
		Guiders	Hinge		pivot, axis, pin, hold down, jam, post, peg, dowel	
	Diode					A semiconductor device which allows current to flow in only one direction.
	...					
	Connectors	Couplers				
Mixers						
...	...					

The individual component terms and associated definitions represent the different “species” of components. Definition of these terms is critical to the usefulness of the ontology proposed. In animal classifications, disagreements exist over how narrowly to define different species, i.e. whether to identify species based primarily on minor differences (splitters [40]) or major differences (lumpers [40]). Similar questions become valid when defining new or existing component terms. For example, should an axle and a drive shaft be classified under the same component term? Should a flexible hose be classified under a different component term than a rigid tube? In the case of the axle and drive shaft, these two components solve different functionality and would, therefore, be placed under different branches of the proposed ontology. The flexible hose and rigid tube are functionally similar, so a decision must be made about whether to group them together under a broad definition or separate them into more specific groups. When defining terms, effort was made to determine whether a new (separate) definition would be beneficial from the perspective of a designer in the early conceptual stages of design, e.g. deciding whether to use a flexible vs. a rigid tube to *transfer* a *material* would be less useful when initially generating concepts than deciding whether to use a *tube* vs. a *conveyor*. To help evaluate whether terms were defined at a low enough level of detail, additional consideration was made as to whether generalities of performance could be made across a component term to help evaluate ideas early in the conceptual phase of the design process.

In general, the initially selected function-based framework worked well to help classify the existing component terms, with two notable exceptions. First, as briefly mentioned before, in nearly all cases of a component solving the function of *store*, the function of *supply* was also included. For this reason, the secondary level of the component hierarchy was refined to eliminate the separate designations of a *Storer* and a *Supplier* and instead include the secondary designation of a *Material* or *Energy Supplier*. Secondly, under the primary level term *Convert* in the Functional Basis exists a single secondary level term *Convert*. To eliminate redundancy in the proposed hierarchical ontology, the secondary level term *Converters* was replaced with designations of a *Material*, *Energy*, or *Signal Converter*. The complete component hierarchy can be found in Figure 5.

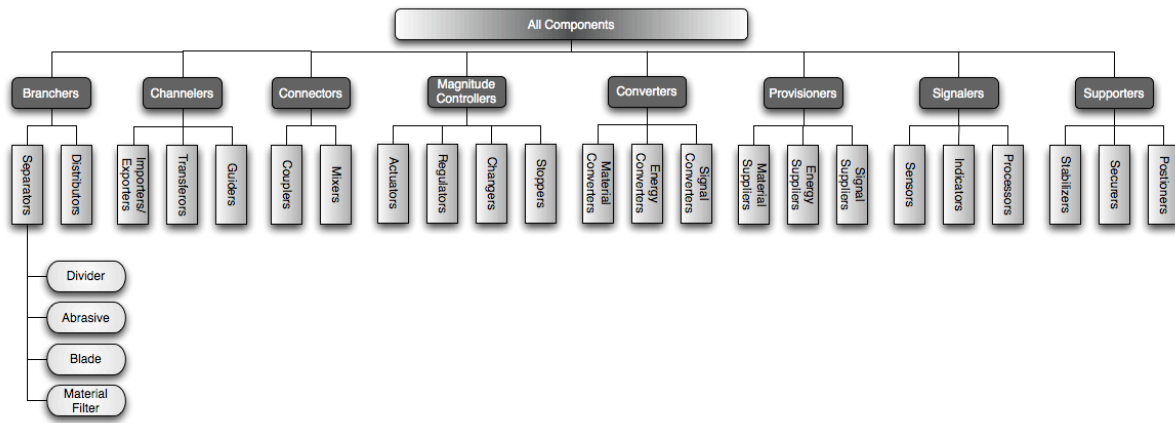


Figure 5. The proposed function-based hierarchical ontology structure. Only the component terms for the class of Separators are shown.

3.3 Classifying Previously Uncategorized Components Under the Ontology

A rigorous procedure was established in order to determine under which component term a previously unclassified component should be grouped within the established hierarchical framework. The procedure developed is as follows:

1. Define the system boundary of the device.
2. Identify all input and output ports of the device across the system boundary defined in step 1.
3. Classify each port as an
 - a. Object port: A device port through which a flow (material, energy, or signal) enters and then travels through the device from the input port to the output port and is processed by the device [33, 39].
 - b. Medium port: A device port through which a flow (material, energy, or signal) enters and then travels through the device from the input port to the output port while holding an object and enabling it to flow through the device (e.g. water can act as a medium carrying hydraulic energy as an object through a device) [33, 39].
 - c. Assembly port: A device port that acts only as a mating surface to support the weight or stabilize the position of the device.
4. Identify the black box functionality of the device and the object flow(s) that it acts on. When defining the black box functionality, the functional purpose of the device should be identified versus the functional embodiment of the device (i.e. the function selected should answer the question “what does this device do?” instead of the question “how does this device work?”) For instance, the functional purpose of a friction brake is to “stop rotational energy” and it does this by “converting rotational energy to thermal energy”. In this case, the black box functionality of the brake would be to “stop rotational energy.”
5. Locate device placement in classification hierarchy.
 - a. Label device using appropriate term.
 - b. If no existing term is suitable, create a new term under the relevant hierarchical category. Generate a definition precisely defining the *form* of the device in a manner that clearly distinguishes the new device from the other components located under the same functional class.

4 DISCUSSION

This paper describes a hierarchical framework that was constructed to help guide the classification of components and extend previously presented work toward a component naming convention that led to a flat list of 114 distinct generic component terms [3]. In addition, the framework presented here uses primary and secondary levels of specification coupled with a robustly defined procedure to help identify the appropriate placement of terms into the hierarchy while maintaining the goals of completeness and exclusivity in component coverage. Under this proposed framework, components of widely varying levels of complexity (e.g. an electric wire vs. an electric motor) may both be placed within the hierarchical structure, as long as the black box functionality may be limited to a single

as measures of potential failures, manufacturability, cost, size, performance, etc.) could be determined across each component group and used to help guide concept selection early in the design process. Other work could include creating a forum for the discussion of new and existing component terms, their placement within the hierarchical ontology, and even the organization of the hierarchical ontology as well. Finally, the work presented here is focused mainly on components found in consumer products. Additional work should look at other design domains and identify how the hierarchy should be altered or expanded to include a broader range of component types. As with the animal groupings, the process to create a complete and robust hierarchy should be an evolutionary process with much discussion involved.

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