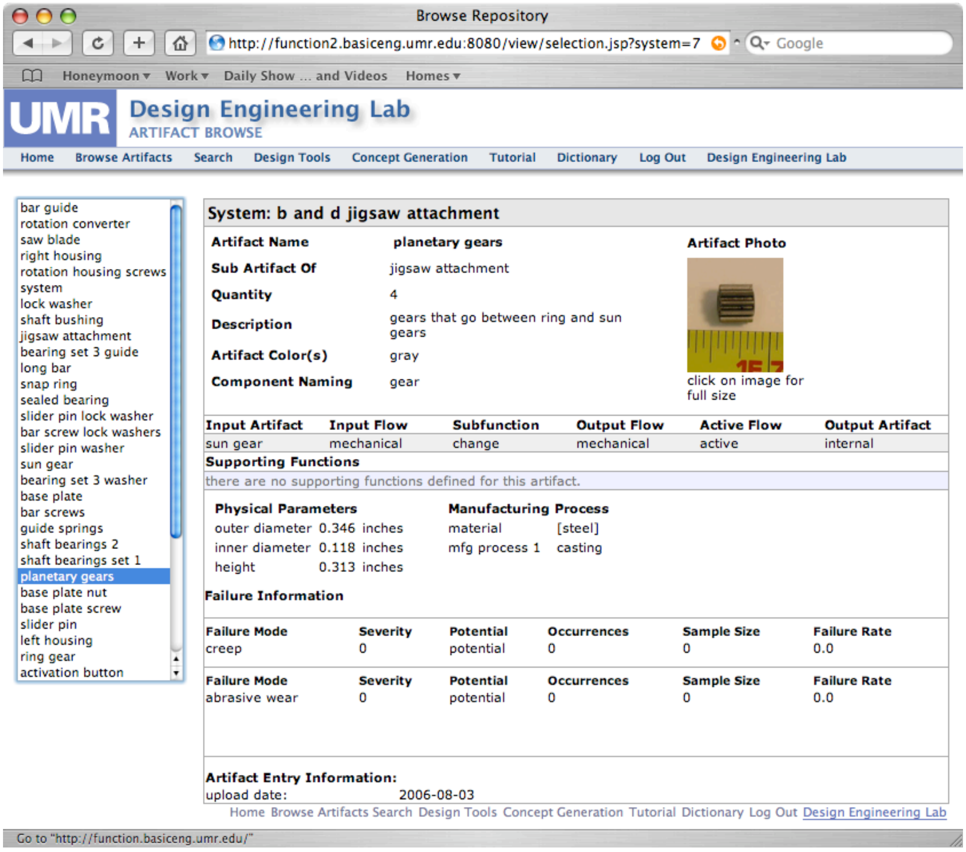

Figure 2. The UMR Design Repository web interface. Entry into the repository may be requested at http://function.basiceng.umr.edu/repository.

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 Linnean 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.

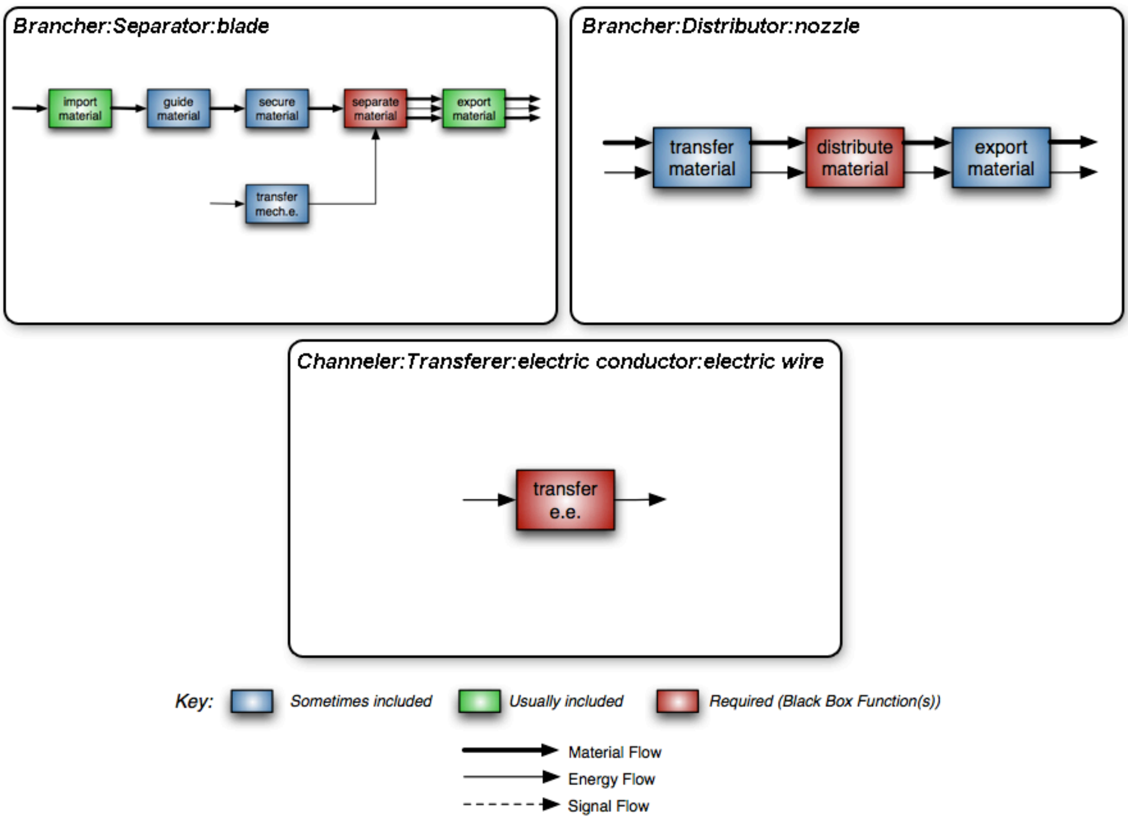

Figure 3. Function templates were used to help establish the functional characteristics of each component term. The templates were constructed using function and flow information entered into the web-based repository described in Section 2.

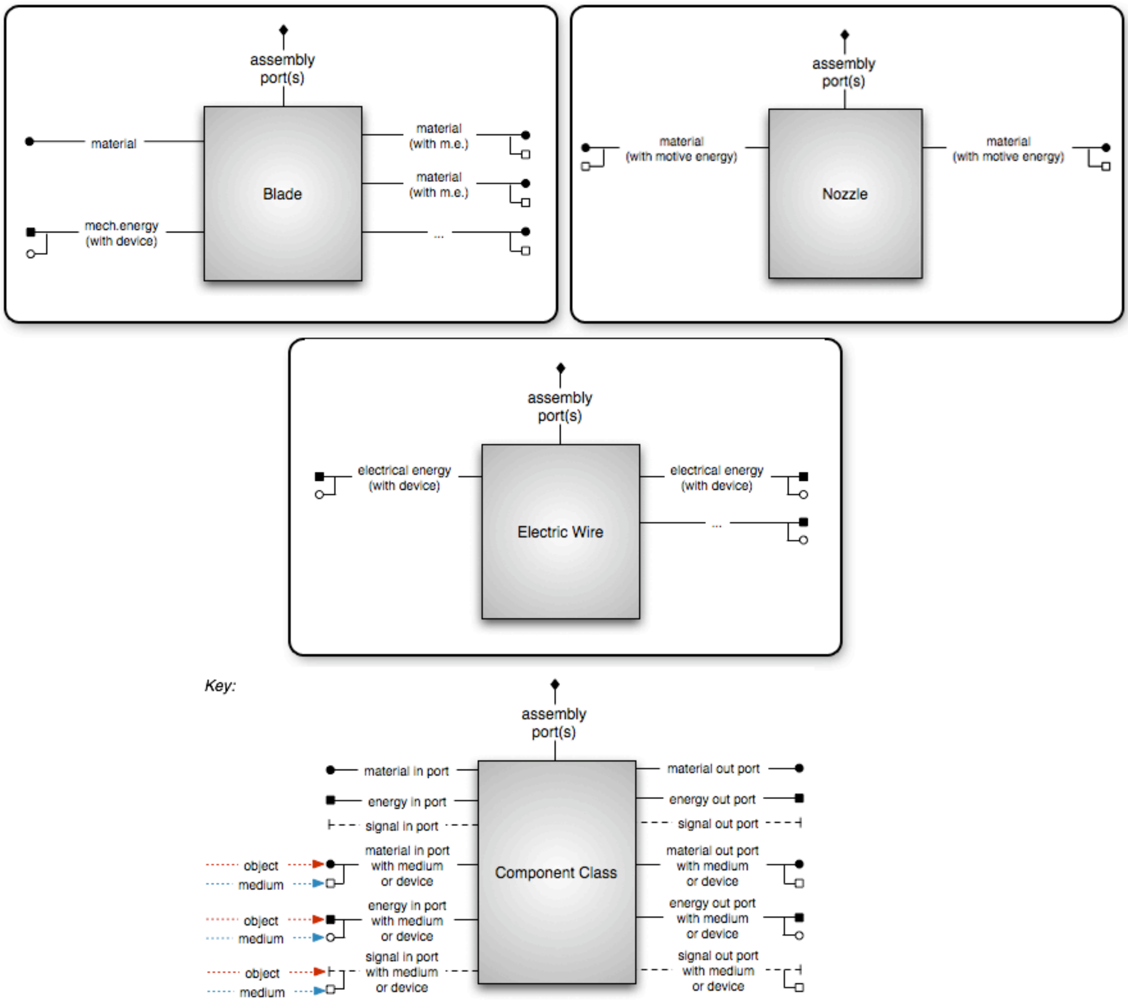

Figure 4. Port templates were also used to help establish the functional characteristics of each component term and to help create distinct definitions for each. Ports are indicated by lines into and out of the component box. Circles represent material flow ports, squares represent energy flow ports, 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	Separaters	...			
	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*	A device that allows rigidly connected materials to rotate relative to each other about an axis, such as the revolution of a lid, valve, gate or door, etc.
		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.

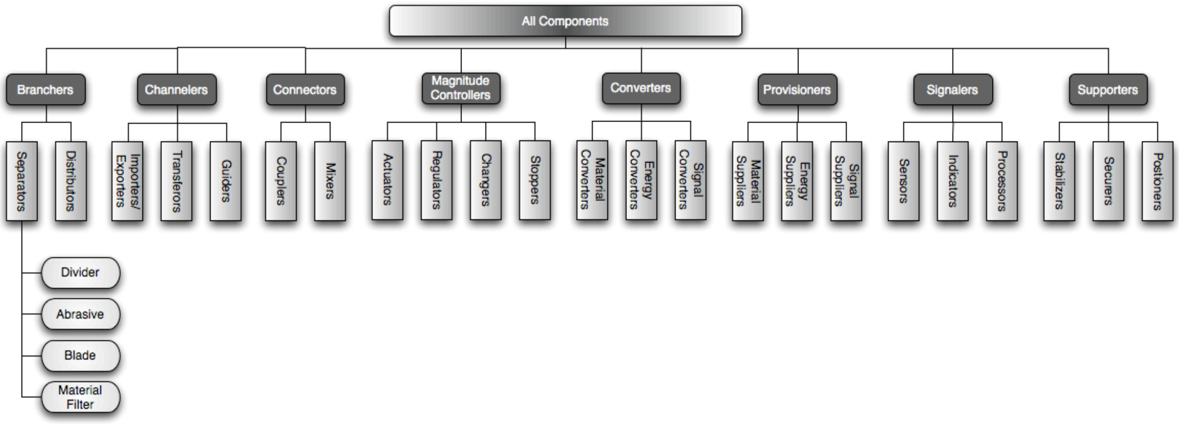

Figure 5. The proposed function-based hierarchical ontology structure. Only the component terms for the class of Separators are shown.

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 function contained within the Functional Basis list of terms. Additionally, components that exhibit functionality directly vital to the functioning of a product (e.g. a plug and cord) are not distinguished from components that only exhibit functionality that supports the function of a product in a more indirect manner (e.g. a bracket that secures an electric motor in place). Finally, although component definitions include references to component form as a way to distinguish between the various component "species", information regarding a component's form or method of manufacture is not used within the component hierarchy. For the components classified thus far, complexity, type of functionality (i.e. whether it directly or indirectly works to solve conceptual functionality), and other characteristics not function related do not seem to negatively impact the effectiveness of the proposed framework. However, as the number of component "species" grows, the proposed framework could be easily adjusted to fit into a larger hierarchical framework where other component characteristics that are deemed appropriate may be added as super-groups to the proposed hierarchy (see Figure 6). As with the classification of living organisms, the classification of components is an endeavour that will be strengthened by discourse.

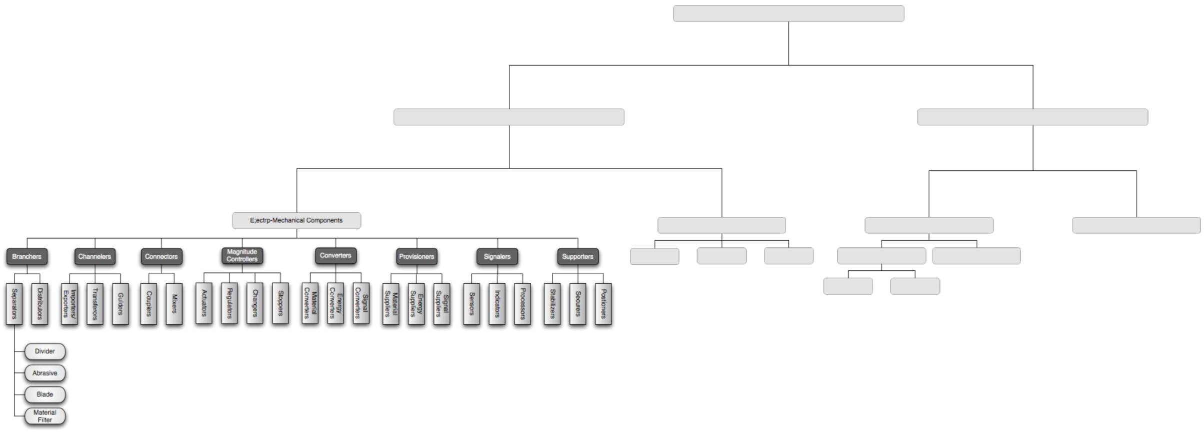

Figure 6. The proposed hierarchy has the potential to be adapted to a larger structure if components from other domains do not fit within the structure proposed for electromechanical devices from consumer products.

In addition to establishing a method of consistently achieving complete and exclusive coverage of the component space, the hierarchical ontology also establishes a means to distinguish traditionally similarly named components that, in fact, have very different functionality. Just as a black-tailed prairie dog (which is, indeed, not a dog at all) and a common domesticated dog could be distinguished as unrelated by their scientific names (i.e. *Cynomys ludovicianus* and *Canis lupus familiaris*), a similar formal naming structure could be used to distinguish common component names that may be misleadingly similar (e.g. a wheel used as a control device to, for example, steer a car vs. a wheel that is fixed to an axle and allows for an object, such as a vehicle, to roll along the ground). As with animal naming, the formal names may be used when clarity of meaning is essential, while the familiar names would not lose their meanings.

Since the primary motivation behind the creation of an effective component ontology is to assist designers during the early phases of design, a hierarchy organized by functional purpose incorporates a level of abstraction that will allow functionally similar but distinct components to be considered for a design. By following the presented procedure and utilizing the proposed hierarchical structure where components are grouped together by functional purpose and distinguished by form and functional embodiment, it is postulated that the goals of completeness and exclusivity of term coverage will also be effectively maintained.

5 FUTURE WORK

To build on the work presented here, future work will include establishing more complete port templates that may be used to help build up more complete conceptual ideas during the early stages of conceptual design. By knowing the number and types of ports a component term typically has, software may be used to help guide the evolution of a full conceptual idea, including parts needed to indirectly support the functionality of other components. Additionally, design measure estimates (such 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.

ACKNOWLEDGEMENT

This material is based upon work supported by the National Science Foundation under grants IIS-0307419 and IIS-0307665. Any opinions, findings, and conclusions or recommendations presented in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

[1] Kusiak, A., Szczerbicki, E., and Vujosevic, R., (1991), "Intelligent Design Synthesis: An Object-Oriented Approach," *International Journal of Production Research*, 29(7): 1291-1308.
[2] Greer J.L., Stock M.E., Stone R.B., Wood K.L., 2003. "Enumerating the Component Space: First Steps toward a Design Naming Convention for Mechanical Parts," Proceedings of ASME DETC & CIE Conferences, September 2-6, 2003, Chicago, Illinois, DETC03/DTM-48666.
[3] Kurtoglu, T., Campbell, M.I., Bryant, C.R., Stone, R.B., and McAdams, D.A., 2005. "Deriving a Component Basis for Computational Functional Synthesis," Proceedings of the International Conference on Engineering Design, August 15-18, Melbourne, Australia.
[4] Strawbridge Z., D. McAdams, R. Stone, "A Computational Approach to Conceptual Design", Proceedings of ASME DETC & CIE Conferences, 2002, Montreal, Canada, DETC2002/DTM-34001.
[5] Bryant C.R., Stone R.B., McAdams D.A., Kurtoglu T., Campbell M.I., 2005. "A Computational Technique for Concept Generation," Proceedings of ASME DETC & CIE Conferences, September 24-28, Long Beach, California, DETC2005-85323.
[6] Kurtoglu, T., Campbell, M., 2005, "Automated Synthesis of Elctromechanical Design Configurations from Empirical Analysis of Function to Form Mapping." Research in Engineering Design, (In Review).
[7] Chakrabarti, A. and Bligh, T., 1996, "An Approach to Functional Synthesis of Mechanical Design Concepts: Theory, Applications and Emerging Research Issues," *Artificial Intelligence for Engineering Design*, Analysis and Manufacturing, 10:313-331.
[8] Campbell, MI, Cagan, J, Kotovsky, K, "A-Design: An Agent-Based Approach to Conceptual Design in a Dynamic Environment," *Research In Engineering Design*. Vol. 11, No. 3, 1999, pg. 172-192.
[9] Bradley, S. and Agogino, A., 1994, "An Intelligent Real Time Design Methodology for Component Selection: An Approach to Managing Uncertainty," *Journal of Mechanical Design*, 116:980-988.
[10] Ward, A., 1989, *A Theory of Quantitative Inference Applied to a Mechanical Design Compiler*, Doctoral Thesis, Massachusetts Institute of Technology.
[11] Ward, A. and Seering, W., 1993, "Quantitative Inference in a Mechanical Design 'Compiler'," *Journal of Mechanical Design*, 115:29-35.
[12] Vadde, S., Allen, J., and Mistree, F. (1995), "Catalog Design: Selection Using Available Assets," *Engineering Optimization*, 25(1): 45-64.
[13] Li, X. and Schmidt, L. (2004), "Grammar-Based Designer Assistance Tool for Epicyclic Gear Trains," *Journal of Mechanical Design*, 126(5): 895-902.
[14] Schmidt, L. and Cagan, J. (1997), "GGREADA: A Graph Grammar-Based Machine Design Algorithm," *Research in Engineering Design*, 9(4): 195-213.
[15] Schmidt, L. and Cagan, J. (1995), "Recursive Annealing: A Computational Model for Machine Design," *Research in Engineering Design*, 7(2): 102-125.
[16] Hubka, V. and Ernst Eder, W., 1984, *Theory of Technical Systems*, Springer-Verlag, Berlin.
[17] Pahl, G. and Beitz, W., 1996, *Engineering Design: A Systematic Approach*, 2nd Edition, Springer-Verlag, London Limited.
[18] Suh, N., 1990, *The Principles of Design*, Oxford University Press.
[19] Ullman, D., 1997, *The Mechanical Design Process*, 2nd ed., McGraw-Hill.

[20] Ulrich, K. and Eppinger, S., 1995, *Product Design and Development*, McGraw-Hill.
[21] Otto, K. and Wood, K., 2001, *Product Design: Techniques in Reverse Engineering and New Product Development*, Prentice-Hall, Englewood Cliffs, NJ.
[22] Liang V, C.J.J Paredis, 2004. "A Port Ontology for Conceptual Design of Systems," *Journal of Computing and Information Science in Engineering*" Vol4, Spetember 2004, pg. 206-217, 2004.
[23] Wallace, A. P., 1995, "The Modelling of Engineering Assemblies Based on Standard Catalogue Components," M.Phil., University of Bath, UK.
[24] Culley, S. J., and Webber, S. J., 1992, "Implementation Requirements for Electronic Standard Component Catalogues," Proceedings Institution of Mechanical Engineers, *Journal of Engineering Manufacture: Part B*, Vol. 206, pp.253–260.
[25] Hicks, B. J., Culley, S. J., and Mullineux, G., 2005, "The Modeling of Engineering Systmes for Their Computer Based Embodiment with Standard Components," *Journal of Mechanical Design*, 127, pp. 414–432.
[26] Gruber, T. R., 1994, "Toward Principles for the Design of Ontologies Used for Knowledge Sharing," *Intl. J. of Human Computer Studies*, 43(5/6): pp 907-928.
[27] Neches, R., Fikes, R., Finin, T., Gruber, T., Patil, R., Senator, T. and Swartout, W. R., 1991, "Enabling technology for Knowledge Sharing," *AI Magazine*, pp 36-56.
[28] M. (editor) Uschold. Knowledge level modeling: Concepts and terminology. *Knowledge Engineering Review*, 13(1), 1998. Also available as AIAI-TR-196 from AIAI, The University of Edinburgh.
[29] Chenhall, R. G., 1978, *Nomenclature for Museum Cataloging: A System for Classifying Man-Made Objects*, Amer. Assoc. for State and Local History, Nashville, TN.
[30] Linnaei, Caroli, 1937, *Determinationes In Hortum Siccum Joachimi Burseri: the text of the manuscript in the Linnaean collections*, ed. Spencer Savage, Printed for the Linnaean Society by Taylor and Francis, London.
[31] Stahovich, T. F., Davis, R., Shrobe, H. "An Ontology of Mechanical Devices," AAAI-93, Working Notes, Reasoning About Function, pp. 137-140.
[32] Paredis, C. J. J., Diaz-Calderon, A., Sinha, R., Khosla, P. K., 2001, "Composable Models for Simulation-Based Design," *Engineering with Computers*, 17: 112-128, Springer-Verlag, London.
[33] Hirtz J.M., Stone R.B., McAdams D.A., Szykman S., Wood K.L., 2002. "A Functional Basis for Engineeering Design: Reconciling and Evolving Previous Efforts," *Research in Engineering* Design, 13(2), pp. 65-82.
[34] Stone, R. and Wood, K., 2000, Development of a Functional Basis for Design, *Journal of Mechanical Design*, 122(4):359-370.
[35] Kurfman M.A., Stone R.B., Rajan J.R., Wood K.L., 2001. "Functional Modeling Experimental Studies," Proceedings of ASME DETC & CIE Conferences, September 9-12, Pittsburgh, Pennsylvania, DETC2001/DTM-21709.
[36] Bohm, M., Stone, R. and Szykman, S., 2003. "Enhancing Virtual Product Representations for Advanced Design Repository Systems," Accepted to *Journal of Computer Information Science in Engineering*.
[37] Bohm M.R., Stone R.B., Szykman S., 2004. "Representing Functionality to Support Reuse: Conceptual and Supporting Functions," Proceedings of ASME DETC & CIE Conferences, September 28-October 2, Salt Lake City, Utah, DETC2004-57693.
[38] Hennig, Willi (1979). *Phylogenetic systematics* (tr. D. Dwight Davis and Rainer Zangerl). Urbana, IL: Univ. of Illinois Press (reprinted 1999).
[39] Kitamura, Y. and Mizoguchi, R., 2003. "Ontology-based Description of Functional Design Knowledge and its Use in a Functional Way Server," *Expert Systems with Application*, 24(2):153-166.
[40] Merriam-Webster Online, www.Merriam-Webster.com, copyright 2005 by Merriam-Webster, Incorporated.

Contact: Cari R. Bryant Arnold
University of Missouri-Rolla
Mechanical and Aerospace Engineering Department
G5 Interdisciplinary Engineering Building, Rolla, MO, USA
Phone: (573) 341-4588, Fax: (573) 341-6593
Email: crb5ea@umr.edu