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EVOLVING A FUNCTIONAL BASIS FOR ENGINEERING DESIGN

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ABSTRACT

All products and artifacts are designed for a purpose. There is some intended reason behind their existence: the product or artifact function. Functional modeling provides an abstract, yet direct, method for understanding and representing an overall product or artifact function. Function modeling also provides a strategy for problem decomposition, physical modeling, product architecting, concept generation, and team organization. A formal function representation is needed to support function modeling, and a standardized set function-related terminology is necessary to achieve repeatable and meaningful results from such a representation. We refer to this representation as a functional basis; in this paper, we seek to reconcile and integrate two independent research efforts into a significantly evolved functional basis. These efforts include research from the National Institute of Standards and Technology (NIST) and two U.S. universities, and their industrial partners. The overall approach for integrating the functional representations is developed, in addition to the final results. The integration process is discussed relative to differences, similarities, insights into the representations, and product validation. Based on the results, a more versatile and comprehensive design vocabulary is obtained. This vocabulary will greatly enhance and expand the frontiers of research in design repositories, product architecture, design synthesis, and general product modeling.

1 INTRODUCTION

1.1 Scope

In engineering design, the end goal is the creation of an artifact, product, system, or process that performs a function or functions to fulfill customer need(s). Conceptualizing, defining, or understanding an artifact, product, or system, in terms of function, is a fundamental aspect of engineering design (Pahl and Beitz, 1984; Ullman, 1997; Ulrich and Eppinger, 1995; Hubka et al., 1988; Otto and Wood, 2001). Figure 1 illustrates two products with functional labels associated with their physical embodiments. These types of representations provide for an abstraction to conceptualize and evolve designs. They also apply to many stages of the product or artifact development process: product architecture, concept generation, and physical modeling as examples.

In this paper, we extend the basic understanding of function in engineering design. Specifically, we explore the differences and similarities among two prior efforts to create a functional basis (Little et al., 1997/Stone and Wood, 2000; Szykman et al., 1999a). Our hypothesis for this research is that, though developed independently with different immediate goals, these efforts toward understanding function explored the same fundamental issues, and thus should have discernable similarities and complementary and resolvable differences. In addressing this hypothesis, the potential exists to evolve our understanding of functional modeling, and, importantly, to converge to a functional basis that will cover engineering design activities at many scales.

In the remainder of this paper, we present the motivation, background, approach, results and conclusions of this research. As specific motivation, we present several immediate and excit-

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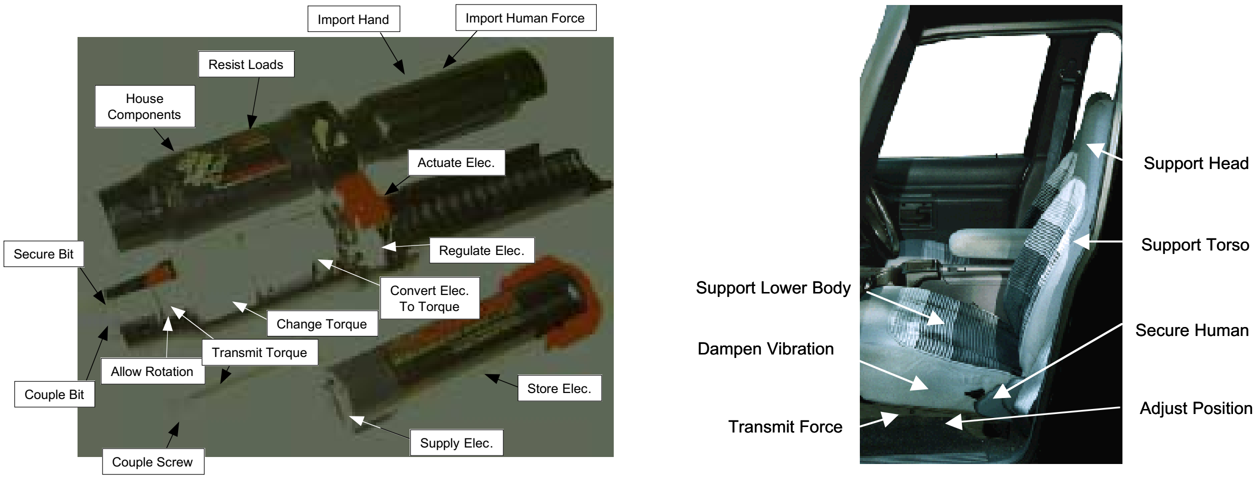

Figure 1. Example Skil[†] Cordless Screwdriver and Automobile Seat with functional labels.

ing applications for a common functional design vocabulary. As background, we briefly summarize the most recent and independent efforts of the authors (Stone and Wood, 2000; Szykman et al., 1999a). The methodology, approach, and specifics of a comparison and resolution effort are then presented. The resulting functional basis is fully documented, and the paper concludes with insights gained from the research process.

1.2 Motivation and Applications

Several factors motivate the creation of a functional basis for mechanical design. What follows are several specific uses for functional modeling. These practical applications serve both as motivation for, and contributions to, the development of a clear and concise functional basis; as the functional basis is used, weaknesses are identified and improvements are made.

Design Repository. The NIST Design Repository Project is an ongoing project at the National Institute of Standards and Technology (NIST) that involves research toward providing a technical foundation for the creation of design repositories—repositories of heterogeneous knowledge and data that are designed to support representation, capture, sharing, and reuse of corporate and general design knowledge. The infrastructure being developed consists of formal representations for design artifact knowledge and web-based interfaces for creating repositories.

Through the course of this project, a variety of research issues have arisen that will in the long term affect the way in which design repositories are implemented and used. These issues include:

1) Development of an information-modeling framework to support modeling of engineering artifacts to provide a more comprehensive knowledge representation than traditional CAD systems.
2) Implementation of interfaces for creating, editing, and browsing design repositories that are easy to use and effective in conveying information that is desired.
3) The use of standard representations, when possible, and contribution to long-term standards development where standards currently do not exist (e.g., representation of engineering function).
4) Development of taxonomies of standardized terminology to help provide consistency in, and across, design repositories, as well as to facilitate indexing, search, and retrieval of information from them.

The degree to which these issues have been addressed, to date, varies within the NIST Design Repository Project. However, these issues are all important to the role of design repositories in industry, and ultimately all will have to be resolved by the research community before design repositories can successfully transition into engineering industrial practice. Other issues, such as security of communications and protection of intellectual property when sharing or exchanging design knowledge, have been recognized but are beyond the scope of this paper.

Within efforts directed toward the development of knowledge representations and vocabularies in this project, there has been a particular focus in the area of engineering function and associated flows. This focus has been driven by requirements articulated at an industry workshop held at NIST, where discussion of the needs associated with representation of engineering function arose in three different breakout sessions. Specific statements indicated (1) a need for representation of function in CAD, in addition to geometry, (2) a need for a fixed representation scheme for modeling function, and (3) a need for a commonly agreed-upon set of functions performed by mechanical systems (Szykman et al., 1998).

Design for Six Sigma with Ford Motor Company. Besides the NIST application, the authors are also working with Ford Motor Company to develop methods for assuring the quality of their products. One such effort is the "Design for Six Sigma" program. The intent of this program is to develop and implement

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[†] Use of any commercial product or company names in this paper is intended to provide readers with information regarding the implementation of the research described, and does not imply recommendation or endorsement by the authors or their organizations.

a repeatable process for producing six-sigma designs with respect to customer needs. An integral component of the program is to create "transfer functions," either analytically or experimentally, that directly measure the customer needs. Functional modeling, as adopted in the program, is a key tool used in the development of these programs. At recent training sessions with engineers across Ford's organization, participants described functional modeling, and associated representations, as a fundamental tool that will greatly assist in the practical implementation of Design for Six Sigma.

General Engineering Design and Product Development. The need for formalized representations in function-based design is often overlooked in the literature; however, it is an issue of critical importance for a number of reasons. The first reason is to reduce ambiguity at the modeling level. Ambiguities can occur when multiple terms are used to mean the same things, or when the same term is used with multiple meanings. The distillation of a large body of terms into a concise basis does not eliminate this problem entirely, but it significantly lessens its occurrence.

A related issue is that of uniqueness, not at the level of individual terms as with synonyms, but at the concept level. The larger the number of terms there are in a vocabulary, the more different ways there are to model or describe a given concept. This makes processing of information that has been represented more difficult, whether it be a human trying to interpret information modeled by somebody else, or whether it be algorithms developed for function-based reasoning or design automation. This problem is mitigated by taking a minimalist approach regarding terminology and formal vocabularies. In practice, it is impossible to have a vocabulary that allows all concepts to be modeled, in only one unique way, because it is the flexibility required for representation of a broad set of concepts that results in multiple ways of expressing the same concept. However, to whatever extent ambiguity problems at the concept level can be reduced, interpreting information that is represented can be made easier.

A third reason for developing a functional basis is that it increases the uniformity of information within functional models. This uniformity will facilitate the exchange of function information among distributed researchers and developers, and will greatly simplify the task of indexing and retrieving information for the purposes of function-based searches and query capabilities.

Several other justifications exist for formal representations of function for engineering design. These include increasing the expressiveness of designers for exploringe and communicating designs, creating early and repeatable physical models of products at a high-level of abstraction, decomposing design problems into realizable sub-problems, systematically searching for analogies to solve design problems, and synthesizing designs with computable formulations (Antonsson and Cagan, 2001). These justifications underscore the expanding frontiers offered by the continued development of a functional basis.

2 BACKGROUND AND RELATED WORK

2.1 Functional Modeling Research

The functional basis research draws its inspiration from prior work in Value Engineering dating back to the 1940s (Miles, 1972; Akiyama, 1991; VAI, 1993). Value Engineering assigns a fraction of the product's cost to each of the elemental functions describing the overall product function. The end goal is to redesign high-cost functions to reduce overall product manufacturing cost. Active verb-object descriptions are given for different product domains to describe a product's function, though no single comprehensive list exists.

Other researchers have recognized the importance of a common vocabulary for broader issues of design. To accurately archive and retrieve helicopter failure information, Collins *et al*. (1976) develop a list of 105 unique descriptions of mechanical function. Here, the mechanical function descriptions are limited to helicopter systems, do not utilize any classification scheme nor do they discriminate between function and flow.

In modern, systematic, function-based design methodologies the search for a consistent functional vocabulary is motivated by the related needs of a clear stopping point in the functional modeling process and a consistent level of functional detail. Pahl and Beitz (1984) list five generally valid functions and three types of flows at a very high level of abstraction. Hundal (1990) formulates six function classes with more specific functions in each class, but does not exhaustively list mechanical design functions. Another approach uses the 20 subsystem representations from living systems theory to represent mechanical design functions (Koch et al., 1994). Kirschman and Fadel (1998) propose four basic mechanical functions groups, but vary from the standard verb-object sub-function description popular with most methodologies. However, this work appears to be the first attempt at creating a common vocabulary of design that leads to common functional models of products.

In a separate development, Soviet Union-era researchers created the Theory of Inventive Problem Solving (TIPS), which describes all mechanical design with a set of 30 functional descriptions (Altshuller, 1984). The TIPS work represents a credible source due to its study of over 2 million patents to formulate its theory and the functional descriptions. Malmqvist *et al.* (1996) compare TIPS with the Pahl and Beitz methodology and note that the detailed vocabulary of TIPS would benefit from a more carefully structured class hierarchy using the Pahl and Beitz functions at the highest level.

More recently, the authors of this paper have worked on two independent research efforts to develop a consistent functional vocabulary. Next we review these independent research efforts prior to presenting the reconciled functional basis.

2.2 The NIST Research Effort

In 1999, as part of work involving the development of a generic representation for product knowledge, researchers at NIST

Conveyance-function
- Advance
- Channel
- Conduct
- Convey
- Direct
- Divert
- Guide
- Generic-move
- Rotate
- Transfer
- Translate
- Transmit
- Transportation

(a)

Channel	Import	
	Export	
	Transfer	
		Transport
		Transmit
	Guide	
		Translate
		Rotate
		Allow DOF

(b)

Figure 2. Excerpts (partial listings) of the (a) NIST and (b) Functional Basis Representations

undertook an effort to develop generic taxonomies of engineering functions and associated flows (Szykman et al., 1999a). In this context, a taxonomy is a hierarchical classification of terms. The intent of these taxonomies of terms was to provide a classification of types that would be associated with various knowledge entities (which can be thought of as data structures) within the product knowledge representation. In addition to engineering functions and associated flows, other knowledge entities include artifacts, behaviors, forms, and others (Szykman et al., 2001).

This paper focuses on that portion of the NIST research that involved the concepts of function and flow. The aim of that work was to generate taxonomies that are as atomic as possible, yet generic enough to allow modeling of a broad variety of engineering artifacts. An excerpt of the NIST function taxonomy is shown in Figure 2a. The representation was developed to provide an infrastructure to facilitate the capture and exchange of function information among researchers at present, and eventually in industry by contributing to interoperability between design systems, be they commercial or developed internally within a company.

The organization of the NIST flow taxonomy follows a traditional approach set forth by Pahl and Beitz (1984) whereby flows are divided into material, energy and signal flows. It is important to note that the categorizations used in the taxonomies are not unique, but are rather a matter of convenience. The organization of the taxonomy is a particular instance of a view of the terminology it contains. For example, the flow taxonomy is broken down by domain (mechanical, electrical, thermal, etc.), each having various terms hierarchically below them. However, an alternative categorization could have organized them by the mapping of variable types across domains. The importance is placed on the content of the taxonomy rather than the specific approach to organizing the terms.

An extensive review of the literature yielded a large body of function- and flow-based terminology within the context of engineering function. From these bodies of terminology, an extensive list of functions and related flows was extracted. The lists of functions and flows were then distilled into considerably smaller ones by removing synonyms, by eliminating functions that were specializations of more generic functions, and by eliminating flows that were specializations of more generic types of flows. The lists of functions and flows were then categorized hierarchically and organized into taxonomies. The taxonomies developed at NIST contain over 130 functions and over 100 flows. Additional details regarding the process of developing these taxonomies are presented in (Szykman, et al., 1999a), as are the full function and flow taxonomies themselves.

2.3 The Functional Basis Effort

The functional basis research grew out of the need for different researchers to describe and compare products functionally. It also grew out of the need to create a formal function representation that would advance design methods and lead to repeatable models.

To describe a product's functionality, an extension to the Pahl and Beitz function structure approach was developed. However, different researchers would represent the same product's functionality with a different set of terms making design communication, modeling, and computation difficult. To alleviate this problem, Little et al. (1997) first proposed a function and flow representation as part of a product comparison method (refer to Figure 2b). This representation was developed empirically through the study of over 100 products. The flow set adopted the Pahl and Beitz flows of material, energy and signal as their highest level and further specified them into two more detailed categorizations. The function set built on the previous work of Value Analysis and later Pahl and Beitz-inspired functional categorizations to include eight function classes. As with the flow set, the function classes were further broken down into two more detailed levels. The function and flow sets were eventually given the name *functional basis*. The choice of the word basis was intentional. The authors wanted to associate the qualities of a mathematical basis – linear independence and spanning the space – with a functional vocabulary of design.

Stone, et al. (1998, 1999a, 1999b) applied and evolved the functional basis as part of a method to identify modular product architectures. Here the basis gave functional models a common vocabulary and identified a stopping point for decomposition by specifying that function and flow words be chosen from a certain level. Definitions for the flow set were first introduced in this work as well (Stone, 1997). McAdams et al. (1999a) applied the functional basis to product similarity computations. Later, the basis was used as part of a design-by-analogy method (McAdams and Wood, 2000a) and a functional tolerancing method (McAdams and Wood, 1999b). The complete functional basis with definitions for functions and flows was presented by Stone and Wood (1999, 2000), in addition to a study demonstrating its ability to improve repeatability of functional models among different designers studied (Kurfman, et al., 2000).

To date, the functional basis is founded on a number of empirical studies, a wide range of existing and original products, and a number of person-years of effort. (Figure 3 shows a past comparison with the general research field.) This foundation has

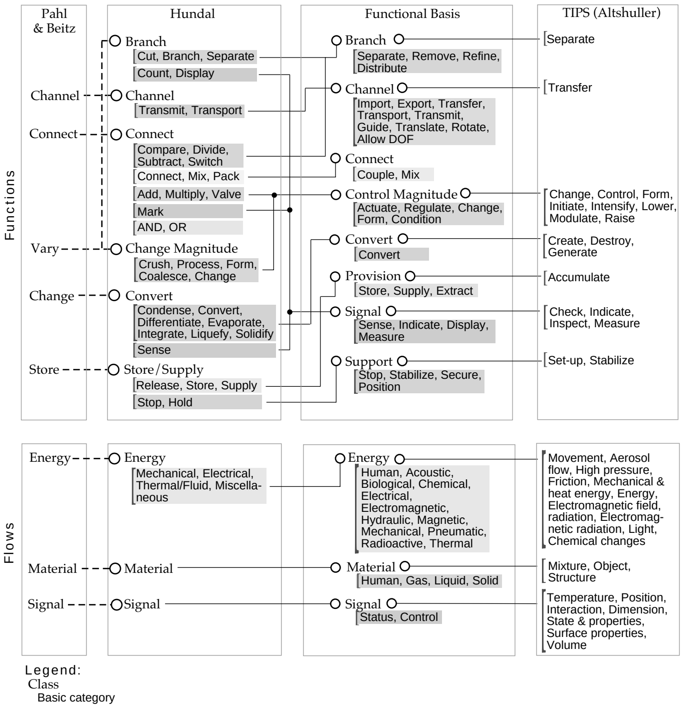

Figure 3. Comparison of earlier function representations with the functional basis.

greatly assisted the development of a number of design methods and solutions to industry design problems. Yet, with each research endeavor, we learn more and converge, asymptotically, toward a more complete and defendable result. The research described in the following section demonstrates a significant step towards this convergence. Through the cooperative and critical integration of two independent efforts, an important evolution of the functional basis is obtained. The positioning of the research among NIST, two universities, and industrial collaborators provides a conduit for its immediate application in practice.

3 RECONCILIATION OF THE NIST TAXONOMY AND THE FUNCTIONAL BASIS

Examination of the two functional vocabularies reveals a high degree of similarity (excerpts in Figure 2). Both research efforts independently attempt to derive a standard list of functions and flows that completely describe the electro-mechanical design space. In order to meet those goals, the authors agreed to take an unbiased, critical look at both vocabularies and to reconcile and integrate the differences.

3.1 General Approach

The intent of the integrated functional basis is that the set of terms at a given level should provide a complete coverage of all concepts within that category. For example, it should be possible to classify any flow into material or signal or energy, and it should be possible to classify any solid material into object, particulate, composite or aggregate.

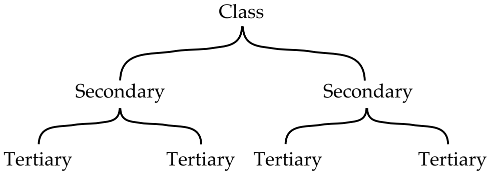

Figure 4. The hierarchical relationship between levels of specification in the functional basis.

During the reconciliation process, a new term is added when it is necessary to do so in order to provide coverage to some area that is not currently fully covered. A new term should appear at the highest level possible such that the new terms and existing terms at that level provide as complete coverage as possible for the category under which the terms appear. This idea is illustrated in Figure 4. The new term must also be mutually exclusive with other terms at that level. If the term is not mutually exclusive but instead overlaps to some degree with a term at that level, then the following categorization algorithm is employed:

1) The new term might be a subset of the existing term it overlaps with, and would therefore be bumped down to the next lower level.
2) The new term might be a superset of the existing term it overlaps with, in which case the new term might replace the existing term and the existing term would be bumped down to the next lower level.
3) The new term might be similar enough to an existing term that it might be categorized as a comparable term (synonym) rather than entering the basis as a new item.

For example, the NIST flow taxonomy did not include "Biological Energy" in its original incantation. It was clear where this flow type would enter the representation. It would not go at the top level, because we do not expect to classify all flows into material OR signal OR energy OR biological energy. Biological energy is a subset of Energy. We would expect to classify all energy flows into Human OR Acoustic OR Biological OR [...]. So it is inserted at the second level of representation.

By developing functional models using different levels of representation, different levels of specification can be developed. These different levels of functional specification are important for several reasons. In the design of new products, the customer needs, and thus functional requirements, are more difficult to ascertain than in a redesign or evolutionary design effort. In general, ambiguous customer needs result in the use of higher-level functions. More specific customer needs lead to the use of more specific types of functions. As in all modeling efforts in design, models should include enough granularity and precision to give designers the information necessary to make a design specification, analysis, or decision.

The two functional vocabularies differ in the naming schemes employed for the levels of specification. Stone and Wood offer a class/basic/flow-restricted (functions) or sub-basic (flow) level identification scheme. In contrast, Szykman et al. do not name the levels to avoid differentiating between the significance of terms at different levels. In both vocabularies, the distinction between the levels has largely the same intent. Therefore, in the reconciled basis we label the three levels (in descending order) as class (or primary), secondary and tertiary. Note that we retained the top-level categorization of *class* that is commonly used in functional modeling literature, but also recognize that this usage of the word *class* is different from that in other fields. As the level number increases, so does the specification of the level. The tertiary level, for example, provides a more specific function and definition than the class or secondary levels, leading to specific technologies or physical principles.

In the previous functional basis efforts, the secondary level is referred to as basic. The secondary functions are intended to be used in the majority of engineering design as well as impart a mathematical connotation of a basis to the second level of functional decomposition. In other words, the basic functions are the smallest functional set spanning the functional space while remaining practical for use. Recognition and inclusion of the tertiary level of functions alters this view. Thus the classification for both functions and flows is unified and presented here as class, secondary, and tertiary.

3.2 Specific Approach

Our specific approach to reconciling the two functional vocabularies followed a three-step algorithm consisting of review, union and reconciliation steps. The approach is shown schematically in Fig. 5 and the steps are described below.

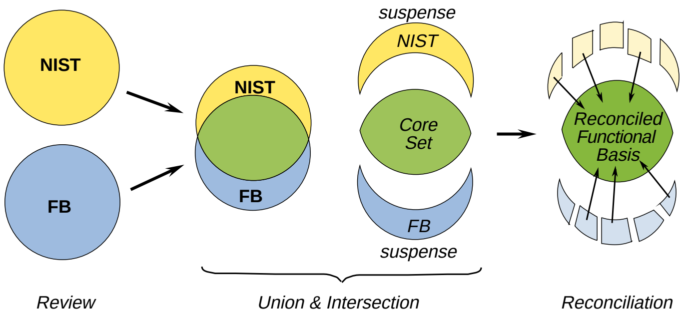

Figure 5. Specific approach followed to reconcile the two functional vocabularies.

Step 1: Review

The latest versions of the functional basis (Stone and Wood, 2000) and the NIST function and flow taxonomies (Szykman et al., 1999a) are reviewed and definitions for each of the function and flow descriptors are formulated (within a product design context).

Step 2: Union and Intersection

The two vocabularies are essentially *unioned* to create a combined list of terms. Those terms that fall in the intersection of the two sets form a core set of terms that are common to both. This unioning process is carried out at each level of the two vocabularies (functions and flows). At this point, a check is made to ensure that the core function and flow descriptors do not overlap in meaning at each level. The function and flow words end up in the difference of the two sets are temporarily placed in a holding category termed “suspense.” Here suspense is used in the bookkeeping sense to indicate a descriptor that is set aside for further review before it is accepted or rejected to the reconciled functional basis.

Step 3: Reconciliation

Using the definitions, each suspense word is initially evaluated at the level it occupied in its original vocabulary. There are two possibilities: 1) If the suspense descriptor is mutually exclusive (i.e. the definition is different from the other words’ meanings at that level) then it is added to the reconciled functional basis at that level. 2) If the meaning of the suspense descriptor overlaps with other words at that level, the categorization algorithm of section 3.1 is applied to find its proper location.

In all cases, the comparison is carried out with respect to product examples. Specifically, we judge a function descriptor’s suitability based on whether or not it describes an operation that a product or device carries out on a flow. This ensures that the reconciled functional basis will consist of only *device functions*, as opposed to *user functions*. For instance, a coffee maker (the device) *imports* the flow of water while a person (the user) *pours* water into the coffee maker.

4 RESULTS

A review of Szykman et al. yields 3 class (primary) flows and 6 class (primary) functions, whereas Stone and Wood yields 3 class (primary) flows and 8 class (primary) functions. On the surface, the two works appear very similar. However, the differences emerge in the number of secondary and tertiary categories. Tables 1 and 2 detail the number of initial secondary and tertiary terms in the two lists of flow (Table 1) and function (Table 2) representations and compare it with the reconciled count. In the two tables, the NIST taxonomies are denoted by NT, the Stone and Wood functional basis is denoted by FB, and the reconciled functional basis is denoted by RFB. As can be seen in Table 2, in some instances one category in the NIST taxonomy corresponded to two separate categories in the original and reconciled function bases.

In general, the NIST function and flow descriptors at the lowest level are more detailed than the lowest level of the functional basis. The secondary level of the functional basis function set proved to be complete, in the sense of spanning a broad set of concepts and remaining non-repetitive, while the NIST taxonomy had more complete secondary flows in terms of material. Through the process of integration, definitions for each representation were compared. Additions to the functional basis resulted in new or evolved definitions. Overlapping flows and functions created integrated definitions or simple refinements.

The reconciled functional basis, resulting from the comparison and combination of the two vocabularies, is shown as Tables 3-4. The reconciled flow set in Table 3 still contains three class

Table 1. Level comparisons between the NIST taxonomy, the functional basis and the reconciled functional basis flow set.

Class (Primary)	Secondary	Tertiary
Material (NT)	8	20
Material (FB)	4	0
Material (RFB)	6	11
Energy (NT)	11	7
Energy (FB)	12	5
Energy (RFB)	12	4
Signal (NT)	3	4
Signal (FB)	2	5
Signal (RFB)	2	7

(primary) flows: material, signal and energy. The material level has five further specified secondary categories with an expanded list of tertiary categories. The signal class has two further specified secondary categories with an expanded list of tertiary categories. The energy class has 13 further specified secondary categories with an expanded list of tertiary categories. To achieve more detail when specifying product information, the power conjugate complements of effort and flow can be used (and are shown in the gray area of Table 3).

The reconciled function set in Table 4 has been modified from having categories of class, basic and flow restricted (in the original functional basis) to class (primary), secondary, tertiary and Correspondents. The column labeled as “Correspondents” is provided as an aid for mapping from terms that are not in the reconciled functional basis to terms that are. In other words, the terms rigid-body, elastic-body or widget in some other representation would all be mapped to the term *object* in a representation built upon the reconciled functional basis. The words contained within the Correspondents category are merely a means of comparison and are not considered to be a fourth level of terms in the reconciled functional basis. The italicized words in Table 4 are repeated correspondents. For example. allow is a correspondent for both the secondary functions import and regulate. The combined function set now contains eight class (primary) categories with an expanded list of secondary categories and the creation of new tertiary categories. The eight secondary categories are branch, channel, connect, control magnitude, convert, provision, signal and support.

5 USAGE AND VALIDATION OF EARLIER EFFORTS

5.1 Discussion of Usage

Both of the earlier efforts (the NIST taxonomies and the original functional basis) were not developed solely as an information-organizing exercise, but to actively support manual and software based applications of functional modeling methods. Since these initial efforts emerged from projects that addressed different engineering design issues and evolved separately, they both were involved with different modes of usage. This section describes how the reconciled functional basis fits within the context of the two different approaches to using vocabularies for functional modeling.

Table 2. Level comparisons between the NIST taxonomy, the functional basis and the reconciled functional basis function set.

Class (Primary)	Secondary	Tertiary
Usage-function (NT)	3	0
Provide (FB)	3	0
Provision (RFB)	2	2
Combination/distribution-function (NT)	10	0
Branch (FB)	4	0
Connect (FB)	2	0
Branch (RFB)	3	5
Connect (RFB)	2	3
Transformation-function (NT)	10	0
Convert (FB)	1	0
Convert (RFB)	1	0
Conveyance-function (NT)	13	0
Channel (FB)	4	0
Channel (RFB)	4	5
Signal/Control-function (NT)	32	0
Signal (FB)	4	0
Control Magnitude (FB)	3	0
Signal (RFB)	3	4
Control Magnitude (RFB)	4	8
Assembly-function (NT)	21	0
Support (FB)	4	0
Support (RFB)	3	0

The reconciled functional basis is flexible enough to form functional descriptions that follow the standard *verb-object* format as well as other formats. In the case of the Pahl and Beitz verb-object format, a function descriptor occupies the verb spot while a flow descriptor fills the object spot. Other formats are possible as long as the function and flow descriptors are expressed correctly at the desired level of specification. Specifically, a function descriptor can be selected from any of the three levels depending on the specification desired. Flow descriptors may be formed at all levels as well. A class (primary) flow is simply the class descriptor, such as *material*. A secondary flow is described by a secondary descriptor + a class descriptor. For example, *human energy* is a secondary flow. Tertiary flows are described by a tertiary descriptor + a class descriptor. An example is the flow *auditory signal*.

If additional energy flow specification is needed at the level of performance variables, then power conjugate complements may be used. A list of power conjugate effort and flow analogies is given in the shaded portion of the energy flow category of Table 3. The product of the effort and flow analogies is either power or a value scalable to power in the case of pseudo-efforts and flows. Here the flow description is formed by a secondary or tertiary descriptor + a power conjugate term. A more specific description of human energy used by a product such as a power screwdriver is *human force*. A few special cases exist where complements stand alone in describing a flow. Stand-alone power conjugate complements are denoted by *italics* in Table 3. Taking an engine,

Class (Primary)	*Secondary*	*Tertiary*	*Correspondents*	
Material	Human		Hand, foot, head	
	Gas		Homogeneous	
	Liquid		Incompressible, compressible, homogeneous	
	Solid	Object	Rigid-body, elastic-body, widget	
		Particulate		
		Composite		
	Plasma			
	Mixture	Gas-gas		
		Liquid-liquid		
		Solid-solid	Aggregate	
		Solid-Liquid		
		Liquid-Gas		
		Solid-Gas		
		Solid-Liquid-Gas		
		Colloidal	Aerosol	
Signal	Status	Auditory	Tone, word	
		Olfactory		
		Tactile	Temperature, pressure, roughness	
		Taste		
		Visual	Position, displacement	
	Control	Analog	Oscillatory	
		Discrete	Binary	
			Effort analogy	***Flow analogy***
Energy	Human		Force	Velocity
	Acoustic		Pressure	Particle velocity
	Biological		Pressure	Volumetric flow
	Chemical		Affinity	Reaction rate
	Electrical		*Emf*	*Current*
	Electromagnetic	Optical	Intensity	Velocity
		Solar	Intensity	Velocity
	Hydraulic		Pressure	Volumetric flow
	Magnetic		*Mmf*	*Magnetic flux rate*
	Mechanical	Rotational	*Torque*	*Angular velocity*
		Translational	*Force*	*Linear velocity*
	Pneumatic		Pressure	Mass flow
	Radioactive/ Nuclear		Intensity	Decay rate
	Thermal		*Temperature*	*Heat flow*
Overall increasing degree of specification →				

Table 3. Functional basis reconciled flow set.

for example, we may be interested in the *torque* produced by the engine instead of the more cumbersome rotational torque.

The degree of specification depends on the type of design and customer needs. Using a more general flow description produces a generic function structure and a wider range of concept variants. However, if customer needs dictate concreteness in flows, then an increasingly specific level is more valuable.

Clear definitions are developed for all flow and function categories. An example of each is also included for clarity. Definitions and examples for the flows and functions are available at http://function.basiceng.umr.edu/fb/main.html (Hirtz et al., 2001).

The NIST work in developing taxonomies was part of a larger effort aimed at developing a standardized representation of function. The work was done in order to enable the implementation of software tools that support functional modeling, and to provide a common basis for the exchange of function-based information among individuals or teams involved in distributed collaborative product development. The need for a standardized representation of function was motivated in part by industry needs (as described in Section 1.2), and also by lessons learned from very costly interoperability problems that have emerged with the widespread use of geometric CAD in industry.

The NIST research set forth an initial specification for a standardized representation of engineering artifact function. This includes schemata (information models) for representation of function and associated flows, as well as an initial attempt at developing taxonomies of functions and flows. These taxonomies had been developed in order to support the standardized representation and to provide a basis for knowledge indexing and retrieval, allowing better access to information for the purpose of design reuse. Additional information regarding representation and associated schemata for representing function and flow can be found in (Szykman et al, 1999a).

Since design knowledge is typically stored in some kind of database rather than in plain text files, the generic schemata and taxonomies introduced in may not be best-suited for exchange of information between software systems. To address this issue, mappings of the generic function representation models into the Extensible Markup Language (XML) were developed (Szykman et al. 1999b). The XML specification imposes guidelines on how to structure a document (in this case function data), how to represent schemata, how to make references, etc., providing advantages over, say, a plain text file format for artifact function models. Subsequent research within the NIST Design Repository Project has led to a more expanded representation for product knowledge. This work estends beyond function and flow to also include representation of artifacts and their form, physical decompositions, capture of the mappings between physical structures, functions, and flows, as well as various kinds of relationships among these entities. This product knowledge representation is described in greater detail in (Szykman et al., 2001).

5.2 Supporting Cases and Validation

A number of research and industrial partnership efforts are underway to support our research on the functional basis. Two examples are a NIST Design Repository Project and a new program at Ford Motor Company.

NIST researchers have been validating work under the NIST Design Repository Project both at the interface development level and the knowledge representation level by modeling real-life artifacts using prototype interfaces and a web-based communications architecture. The artifacts modeled at NIST include several power tools (e.g., a power drill, a detail sander, an electric saw),

Table 4. Functional basis reconciled function set.

Class (Primary)	*Secondary*	*Tertiary*	*Correspondents*
Branch	Separate		Isolate, sever, disjoin
		Divide	Detach, *isolate*, release, sort, split, disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, *clear*
		Remove	Cut, drill, lathe, polish, sand
	Distribute		Diffuse, dispel, disperse, dissipate, diverge, scatter
Channel	Import		Form entrance, *allow*, input, *capture*
	Export		Dispose, eject, *emit*, empty, *remove*, destroy, eliminate
	Transfer		Carry, deliver
		Transport	Advance, lift, move
		Transmit	Conduct, convey
	Guide		Direct, shift, steer, straighten, switch
		Translate	Move, relocate
		Rotate	Spin, turn
		Allow DOF	*Constrain*, unfasten, unlock
Connect	Couple		Associate, connect
		Join	Assemble, fasten
		Link	Attach
	Mix		Add, blend, coalesce, combine, pack
Control Magnitude	Actuate		Enable, initiate, start, turn-on
	Regulate		Control, equalize, limit, maintain
		Increase	*Allow*, open
		Decrease	Close, delay, interrupt
	Change		Adjust, modulate, *clear*, demodulate, invert, normalize, rectify, reset, scale, vary, modify
		Increment	Amplify, enhance, magnify, multiply
		Decrement	Attenuate, dampen, reduce
		Shape	Compact, compress, crush, pierce, deform, form
		Condition	Prepare, adapt, treat
	Stop		End, halt, pause, interrupt, restrain
		Prevent	Disable, turn-off
		Inhibit	Shield, insulate, protect, resist
Convert	Convert		Condense, create, decode, differentiate, digitize, encode, evaporate, generate, integrate, liquefy, *process*, solidify, transform
Provision	Store		Accumulate
		Contain	*Capture*, enclose
		Collect	Absorb, consume, fill, reserve
	Supply		Provide, replenish, retrieve
Signal	Sense		Feel, determine
		Detect	Discern, perceive, recognize
		Measure	Identify, *locate*
	Indicate		Announce, show, denote, record, register
		Track	Mark, time
		Display	*Emit*, expose, select
	Process		Compare, calculate, check
Support	Stabilize		Steady
	Secure		*Constrain*, hold, place, fix
	Position		Align, *locate*, orient
Overall increasing degree of specification →			

an ultra-high vacuum artifact transport system,[1] and the new encasements for the Charters of Freedom.[2]

Ford Motor Company has also participated in recent efforts to implement the functional basis. A new program in Design for Six Sigma uses the functional basis as a method to develop critical and repeatable transfer functions to create robust designs. Functional modeling has been received with great enthusiasm and the results show that the functional basis can model the large-scale systems developed by Ford.

6 CONCLUSIONS

In engineering design, functional modeling provides a direct method for understanding and representing an overall artifact func-

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[1] The NIST Artifact Transport System was designed and built at NIST in order to transport atomically-accurate specimens created in a molecular beam epitaxy laboratory to a scanning tunnel microscope laboratory across the NIST campus, where metrologists verify atomic-scale measurements.

[2] These encasements were designed and fabricated in a collaboration between the National Archives and several operating units at NIST to house the Charters of Freedom— the Declaration of Independence, the Constitution, and the Bill of Rights.

tion without reliance on physical structure. In practice, to achieve repeatable and meaningful results from functional modeling, a formal functional representation is needed. This paper represents the reconciliation of two independent efforts to create such formal representations of function.

Both of these efforts were initiated and progressed independently, but were founded on common assumptions. Both groups believed that:

- It was possible to identify a comprehensive set of functions and flows that could be used to model engineering artifacts, products and systems,
- Each of these sets of terms could be distilled to a more fundamental set that would ideally (as it was refined and validated) lead to a minimal set of terms that did not overlap, and yet provided complete coverage of the space of designed products, and
- Identifying these sets of terms would be very valuable to engineers, both by providing a basis to support the use of more formal design methods by people, and to support the development of computer-aided software tools developed for use during conceptual design.

Examining some statistics that came out of the reconciliation effort provides revealing insights as to the validity of these assumptions. One would expect that if there were a fundamental set of functions and flows, two unrelated efforts would begin to converge to the same sets. On the other hand, if there were not one fundamental set of flows but many alternative sets, two independent efforts would more likely converge to different sets. At the gross level, one can examine the independently-developed sets of functions and flows (Stone and Wood, 2000; Szykman et al., 1999a) and note that there is a high degree of similarity at the top levels of the hierarchies. One can also do a more detailed comparison by examining the commonality between the reconciled functional basis and the earlier works.

Of the 42 terms in the reconciled flow set (Table 3), 34 are present in the NIST function taxonomy either as exact matches or equivalent terms. A significant portion of this discrepancy can be attributed to the fact that the earlier NIST work considered the human as being “outside of the system,” resulting in the absence of the Human terms and all of the terms associated with human senses (i.e., Auditory, Olfactory, Tactile, Taste, Visual). Other than the human and human-related terms, there are only 2 terms in the new flow set that did not appear in the earlier NIST work. Similarly, 27 of the terms in the reconciled flow set appear in the original functional basis work. Of the 53 terms in the reconciled function set (Table 5), 46 are present in the NIST function taxonomy as exact matches or equivalent terms; in the original functional basis work, 47 of them are present.

From this perspective, it can be seen that the terms in the reconciled function and flow sets were covered by both sets of earlier work to a significant degree. Among the more significant differences between the two earlier efforts themselves (as opposed to the reconciled basis and earlier work) was the size of the sets of terms, the NIST taxonomies being considerably larger than the original functional basis. This is primarily due to a fundamental difference in approach; the NIST effort attempted to provide a comprehensive list of function and flow terms used by engineers, whereas the original and reconciled functional basis attempt to minimize terms. Many of the terms that were originally in the NIST taxonomies are now listed among the correspondents. Thus, while these terms are not counted when tallying the total number of fundamental function and flow terms in the reconciled basis, the breadth of terminology used by engineers and information about the relationships between terminology and the fundamental sets of terms, is still preserved.

There are a number of important contributions of this research. By combining these two function vocabularies, we have evolved our understanding of functional modeling and created a taxonomy that supports engineering design at many scales. Also, the rigorous review of the previous function taxonomies has sharpened the distinctions between the function and flow descriptors.

Another important contribution, and key goal of this paper, is the evolved definitions (Hirtz et al., 2001). These definitions result from a number of empirical studies over a wide range of existing and original products, a number of person-years of effort, and independent research efforts. The formality of the reconciled functional basis facilitates engineering design education in both university and industry settings. Functional models are more easily reviewed for either similarity or correctness. Also, they can be developed at different levels of precision, offering enough abstraction for original design problems and enough detail for redesign or documentation of existing products.

Though additional research at a basic level would likely contribute to the functional taxonomy presented here, we see the next evolution of the reconciled functional basis to occur through usage. The reconciled functional basis provides a foundation for design repositories, support for new knowledge-based design methods such as design by analogy, design for manufacturing and product architecture, and a teaching tool for design education and training. As it is used in these endeavors, we expect the reconciled functional basis to slowly evolve and mature. Thus, one of the important results of the research presented here is a process for adding new descriptors to the reconciled functional basis.

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