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The Need for a Form, Function, and Behavior-based Representation System

Edward Chang
changman@eng.umd.edu

Xin Li
lixin@glue.umd.edu

Linda C. Schmidt*
lschmidt@eng.umd.edu

Designer Assistance Tool laboratory
Department of Mechanical Engineering
University of Maryland
College Park, Maryland 20742-3035

Abstract
This paper discusses recent developments in the state of design representation systems and proposes a focus for the next step in the evolution of design representation systems. The purpose of the former is to gain an understanding of the status of design representation strategies and their role in design. The purpose of the latter is to outline one promising path for future research in design representation systems. Form, function, and behavior all serve unique and supporting roles in design representation. This reasoning is demonstrated through the use of empirical and theoretical examples. As lone representations of a design, form, function, and behavior based perspectives have inadequacies; by taking all three in combination, a more robust and complete representation system can be realized.

1 Introduction
Mechanical design knowledge is synthesized, expressed, and maintained as a collection of representations of the concept designed. Certain design activities require viewing the design through a specific perspective. A perspective is a model of a design that must be built, reconciled with new information, and revised throughout the design process (Cowan et al. 1999). Consider that the testing of a product casing's structural integrity can be done with finite element analysis; FEA requires a representation of the casing as a mesh. A design representation system translates a concept into a type of perspective, using a predefined syntax, semantics, and parameter set.

The needs and capabilities of design analysis tools motivate changes in the use of design representation systems. Form representation technology has advanced to the point where digital 3D models serve the same role in the creative process as pencil and paper sketches were used in the past. Similar changes in other types of representation systems occur because of advances in analysis capability of digital models. The ability to analyze design behavior under a variety of conditions drives the need to model a design analytically to gain feedback on likely or potential behavior before design decisions are made. As analysis tools improve, advances in computational equipment give designers access to more accurate data throughout the design process. The access and potential benefit of improved behavior puts pressure on designers to anticipate and reflect more of

* Corresponding author

an artifact's behavior during the earliest stages of design. As result, design has more of a dynamic nature about it.

Effective designing requires a representation strategy to guide the type of perspectives developed and at what point in the process they are created. A system that can integrate the different types of perspectives needed for effective design would be ideal for today's designers. What is presented here is a framework for such a system. This system takes existing knowledge about design representation and proposes a direction for this knowledge to be integrated with each other. Furthermore, examples are shown to demonstrate the inadequacies of individual perspectives and the satisfaction of design needs by an integrated system.

The paper outlined as follows: Section 2 describes previous work done in the area of design representation systems; Section 3 proposes the framework of integrated perspectives; Section 4 offers discussion and examples; and Section 5 concludes the paper.

2 Previous Work

2.1 Overview and definition of terms

Representation systems used to only exist in the minds of designers. The designer's system was adequate because he only needed to convey the idea to himself. With the advent of information sharing, there was a need for a more effective way of conveying design knowledge. Three main perspectives were studied during this effort: form, function, and behavior. The three terms have undergone a variety of definitions and are defined here for the sake of clarity of use in this paper. Form perspectives, most often created by CAD packages, rely on geometric rules to interpret designs (Zhang 1999). Function perspectives are based upon intended transformations between inputs and outputs (Pahl and Beitz 1977 and 1996, Szykman 1999, and Bogoni 1998). Behavior perspectives are based upon all physical relations, whether or not they are intended or not (Gero 1991 and Karnopp and Rosenberg 1975). It can be seen that function is a subset of behavior.

For a general overview of representation systems, Finger and Dixon (1989[1] and 1989[2]) examine over 250 representation systems and interject general comments about the nature of design representation. Since then, many other representation systems have been developed. Function and form have been the predominant area of research and some systems have gone beyond that to include behavior to some extent.

2.2 Form and function-based representations

Form and function representation systems have received a high level of maturity. Four such examples are Pahl and Beitz (1977 and 1996), Chakrabarti (1994), Callahan and Heisserman (19XX), and Szykman (1999).

Stone and Wood (1999) propose a functional basis language that offers more consistency than previous systems. The basis uses a verb-object format to describe all artifacts in the mechanical and electro-mechanical domains. The basic flows proposed by Pahl and

Beitz, and later refined by Hundal (1997), are broken down into more specific terms to form a taxonomy. In addition to encompassing the above three authors' systems, the basis also reflects the 30 functional descriptions of Altshuller's Theory of Inventive Problem Solving (1984).

2.3 Research in behavior perspectives

While some researchers have been studying form and function, others have developed systems that have utilized behavior in lieu of or to support form or function. Karnopp and Rosenberg (1975) developed the foundation of behavior-based representation with bond graphs. Umeda et al. (1990) look at representation as a combination of function, behavior, and state; the addition of behavior helps to alleviate some of the issues of form and function-based systems. Gero et al. (1991) proposes that behavior is the link between function and form (called structures in their work) in design and develops a framework that utilizes behavior. They conclude that behavior "serves as a platform of reasoning between the two." A similar concession is made by Szykman (1999) and consequently, his system allows for a behavioral component to be added in at a later date.

3 Proposed Framework

The FFB (form, function, behavior) framework proposed here is an integrated system using form, function, and behavior based perspectives to fully describe any and all artifacts at any time during the design process from conceptual design to detail design. The three perspectives collectively use their individual strengths to support design representation and to back up individual weaknesses. These strengths and weaknesses are discussed in Section 4. In order for this type of system to be feasible, it must also be integrated into the design processes that are utilized by various engineers.

Though there are many different design processes in use today, most are essentially the same differing only in terminology (Thomson, 1992). Invariably, there are two main stages: conceptual design and detail design. Processes used by Clausing (1994), Dixon & Poli (1995), Hundal (1997), Magrab, Pahl & Beitz (1977 and 1996), Suh (1990), Thompson (1992), Ullman (1997), and Ullrich & Eppinger (1995) all incorporate conceptual and detail phases. Function, form, and behavior all have their places in design and a system with an FFB framework will help to support each phase.

Function, as stated above, gives the design direction and research has promoted the usage of function-based perspectives as the language for conceptual design. The product concept is an approximate description and functions allow for the most modularity at this point (Ullrich and Eppinger 1995). Conceptual design success is predicated upon the ability to articulate and manipulate function models of artifacts. A naïve understanding of conceptual design may lead one to believe that a function perspective of an artifact is adequate. However, any realistic conceptual design review process demands that the designer be able to answer performance questions that arise from secondary characteristics of a design, better known as behavior. Understanding and predicting behavior is the key to creating designs that react with its environment. Behavior, other than intended behavior, is not modeled directly during the conceptual design phase because the focus is on assuring and improving functionality, which is a subset of possible behaviors.

When the focus of the process switches to the detail design phase, form and behavior perspectives begin to play a more prominent role. A form representation, one that can be tested under use conditions to give accurate performance data, can embody functionality and help give valuable feedback when used with behavior. Many behaviors are taken into account due to the interactions between subsystems (Pahl and Beitz 1996), but prototyping and simulating is required to detect unanticipated phenomena (Ullrich and Eppinger 1995). Form perspectives can also give a definitive look at the physical makeup of an artifact. As can be seen by the description above, the focus of design changes throughout the process and thus the most useful representation view changes, as well.

The designer determines what kind of perspective should be used at a particular time. The three perspectives each take turns being the emphasis of the design while non-emphasized views provide support when necessary. The designer has control over how much support is given and at what times so that the amount of needed information is enough to fully describe the artifact, but stream-lined enough to prove manageable and useful.

4 Discussion

4.1 Individual perspective-based representations are inadequate

In order to understand why an integrated perspective representation is needed, an analysis into the shortcomings of each perspective when used in isolation is necessary. The following examples will show that, during the conceptual design phase, form is seldom practical, function is never enough, and that behavior is ill defined.

4.1.1 Form is seldom practical

The ease with which we can build digital models of the form of an artifact and our confidence in analysis to reveal the ultimate value of a design encourages us to use form representations in all phases of the design process. Unfortunately, focusing on a form perspective of a design can be premature or impractical. Reliance on form representations alone can handicap a designer via design fixation. An example of this later handicap is the Kansas City Hyatt Regency walkway collapse. The walkway collapse was due to insufficient strength of rod and box beam connections, as seen in Figure 1. Originally, the design had called for a single beam to go the entire height of the 60-foot set of walkways. The design was changed to utilize shorter 15-foot beams, allegedly for ease of construction. The new design was never tested for load conditions (Petrovski 1992). The design change occurred through a form-only perspective. There was no way to see that the walkway was going to fail based upon the perspective. Washers and nuts held each rod in place. The fact that the washers and nuts were subjected to a cumulative stress was not determined from the drawings.

Figure 1 – Failed beam of Kansas City Hyatt Regency walkway

4.1.2 Function is never enough

Function can accurately describe an artifact and give most designers a sense of the nature of the artifact. However, it is not enough to distinguish many artifacts from each other. A class of artifacts can all be described the same way from a functional standpoint. In the case of epicyclic gear trains (EGT), the function is to convert a quantity of rotational motion into a different quantity of rotational motion. A graphical illustration of EGT function using Szykman's method (1999) is depicted in Figure 2. There are many ways to satisfy the given function. The two configurations shown in Figure 3 both satisfy the function despite being different designs. Also, the function of EGT does not specify how the device is used, that is to say that the input and output shafts are not defined. Additionally, there may be non-functional constraints on the design that will not be 'seen' by a function-only representation system.

4.1.3 Behavior is ill defined

A vocabulary or methodology for building full behavior models does not exist. What is commonly done is to build constrained models to carry out the lowest level of analysis

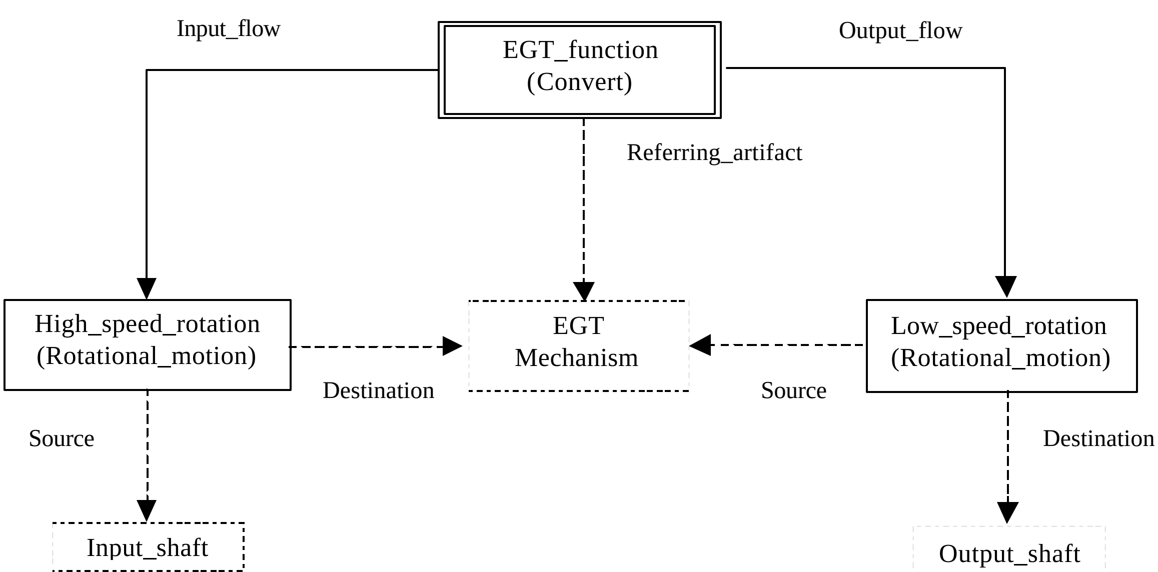

Figure 2 – EGT Functional Schematic via Szykman method (Szykman 1999)

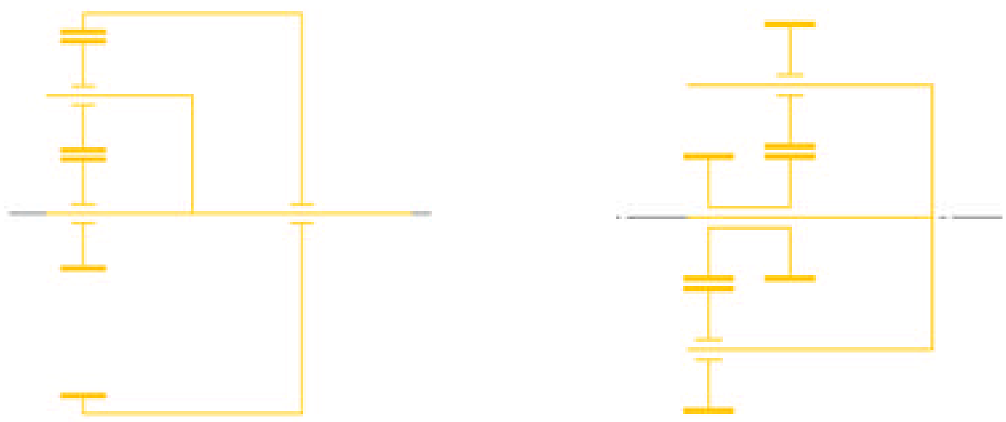

Figure 3 – Two different EGT designs carrying out the same function

possible to make decisions about the design. Behavior models at this stage may be closed form solutions that describe first order effects like the bending of a loaded bar or the resultant forces on a system member. What is learned from these initial analysis models is often carried through the process as constraints of what should be avoided and notes of what functionality to enhance. These constraints are refined throughout the process as more accurate models are built and tested. At the end of the design process, it is usual to have a number of independent behavior models, each tailored for a particular analysis method, and some requiring the development of near-final form views of the design.

The closest systems to date are Karnopp and Rosenberg's bond graphs (1975) and simulations. Bond graphs base their representations on power flow through a system as it obeys the physical laws of that system. While it is useful to understand all physical phenomena associated with a design, there is no focus to the information resulting in wasted effort and resources. Without focus, the designer has no direction with which to use the data to complete the design objective. Under the same reasoning, simulations are not feasible on a large scale because of behavior's lack of direction.

For instance, in designing a bridge, the main concern of is forces. The members must be able to hold with a certain factor of safety. Ideally, the designer would place maximum load conditions on members to ensure success. There is an infinite amount of loading conditions that the engineer could use, including the feasible ones. This leads to an equally infinite amount of data gathered by the designer. The data has no focus and thus there is no determination as to what data are relevant and what can be ignored. Additionally, there may be effects that appear in multi-member structures that are not accounted for in the individual simulations.

4.2 How an FFB integrated perspective will work

4.2.1 FFB satisfies criteria for a complete representation system

Combining form, function, and behavior can satisfy all necessary criteria for a representation system. Bogoni (1998) states that representation can be broken down into functional primitives. Because these primitives are not descriptive enough, the representation should be expanded to include the artifact and the role of the artifact in its environment. An evaluation protocol for functionality was subsequently developed and was modified to evaluate design representation systems. The changes are discussed below.

Three of the characteristics are uniqueness, completeness, and minimality. Uniqueness for functionality is the ability to specify the functional task and this definition was modified for our purposes to define all types of artifacts. Completeness for functionality expresses the perceptual and interactive capabilities of the functional agent; subsequently, this was modified to incorporate all types of artifacts (including the perceptual and interactive characteristics of those artifacts). Functional minimality is the characteristic that allows for a smooth transition between identified functional features and its representation; that is to say that nothing extraneous can be interpreted from the features and the representation does not change. For representation systems, minimality is interpreted as the ability to represent said features with a minimum spanning set. It can be seen that there is some overlap to the characteristics, but it is not significant enough to combine the criteria. Bogoni's three criteria are used to evaluate three candidate representation systems that focus on form (CAD packages), function (Pahl and Beitz function structures), and behavior (simulations). Table 1 illustrates how well each system satisfies Bogoni's criteria.

Table 1 - Evaluation of representation systems based upon Bogoni's criteria (Bogoni 1998)

Bogoni's Criteria	Form: CAD packages	Function: Pahl and Beitz style function structures	Behavior: Bond Graphs
Uniqueness – the ability to represent an individual design in one way	Yes – geometric boundaries allow for any level of physical detail	No –function structures are subjective and can be interpreted differently	No – exercising of physical laws is not the same for representing all phenomena
Completeness – the ability to represent all designs	Yes – all physical artifacts can be represented	Yes – all functions used can be communicated	No – all physical laws are not known
Minimality – the ability to satisfy representation with a minimum spanning set	No – over specificity is possible depending on designer	No – function structures are subjective and can be interpreted differently	Yes – minimal exercising of physical laws is possible for representing all phenomena

It can be seen that the individual views do not satisfy all criteria. However, taking all three together will satisfy the criteria (i.e. there is a 'yes' in each row). Form and behavior taken together can also satisfy the criteria, but function is a subset of behavior and thus is incorporated implicitly.

4.2.2 FFB completely defines indeterminate examples

In Section 4.1, it was demonstrated that individual view-based representations are inadequate. Those same examples are presented again defined through FFB.

The addition of function and behavior views could have helped the designers of the Hyatt walkway. The function of the nuts and washers was to hold the weight of the walkways below. A behavioral analysis would have revealed the cumulative weight of the walkways on the nuts and washers. Subsequently, the conclusion would have been drawn that the design was not safe and the tragedy averted.

Form and behavior add much needed definition to EGTs. Form can help conclusively define an EGT by defining the planet/ring/sun gear structure. Utilizing a behavior model can help to define gear ratios and give the EGT a place in a mechanism.

FFB can support behavior-based systems and completely describe a bridge by giving focus to the resultant data. Once focused, the data can then be useful in redesign or archived. Form and function act in different ways to focus the data. Form gives a physical meaning to the data. The bridge is given a certain configuration and load conditions are placed on certain members. The load itself is given characteristics, as well. Function helps to define what behaviors to take into account, thereby cutting down on the amount of data.

4.3 Value and importance of an FFB system

An accurate form view is always enough for answering any question during the design task but cannot be built at the beginning of a design process and can be too cumbersome to maintain throughout the entire process. As a result, function views are adopted as the surrogate for early stages of the design process. Not only is function a streamlined representation system, as compared to form, but a function view of an artifact prevents designers from focusing too narrow on a solution type and encourages the examinations of concepts from a first-principles perspective. Function views are still focused on the intended behavior of an artifact and cannot express the full range of a design's performance. The ultimate behavior model of any artifact is a full-size, production quality prototype. Before that is available, a variety of behavior models are used to view the likely performance of design alternatives.

Figure 4depicts the relationship between form, function, and analysis models during the mechanical design process. The outer loop shows the interaction of views during the complete process from function to form. The inner loop shows the use of surrogate, and less precise, form and behavior models to perform a conceptual design cycle. The needs of analysis can sometimes remove design efforts from the inner loop of the process. Each time this occurs, there is an increase in design overhead and time needed to complete the process.

Currently, a complete behavior-based representation system is non-existent. Representing behavior is difficult due to the fact that the totality of behavior is more complex than it parts. An FFB system will allow for a more complete representation of

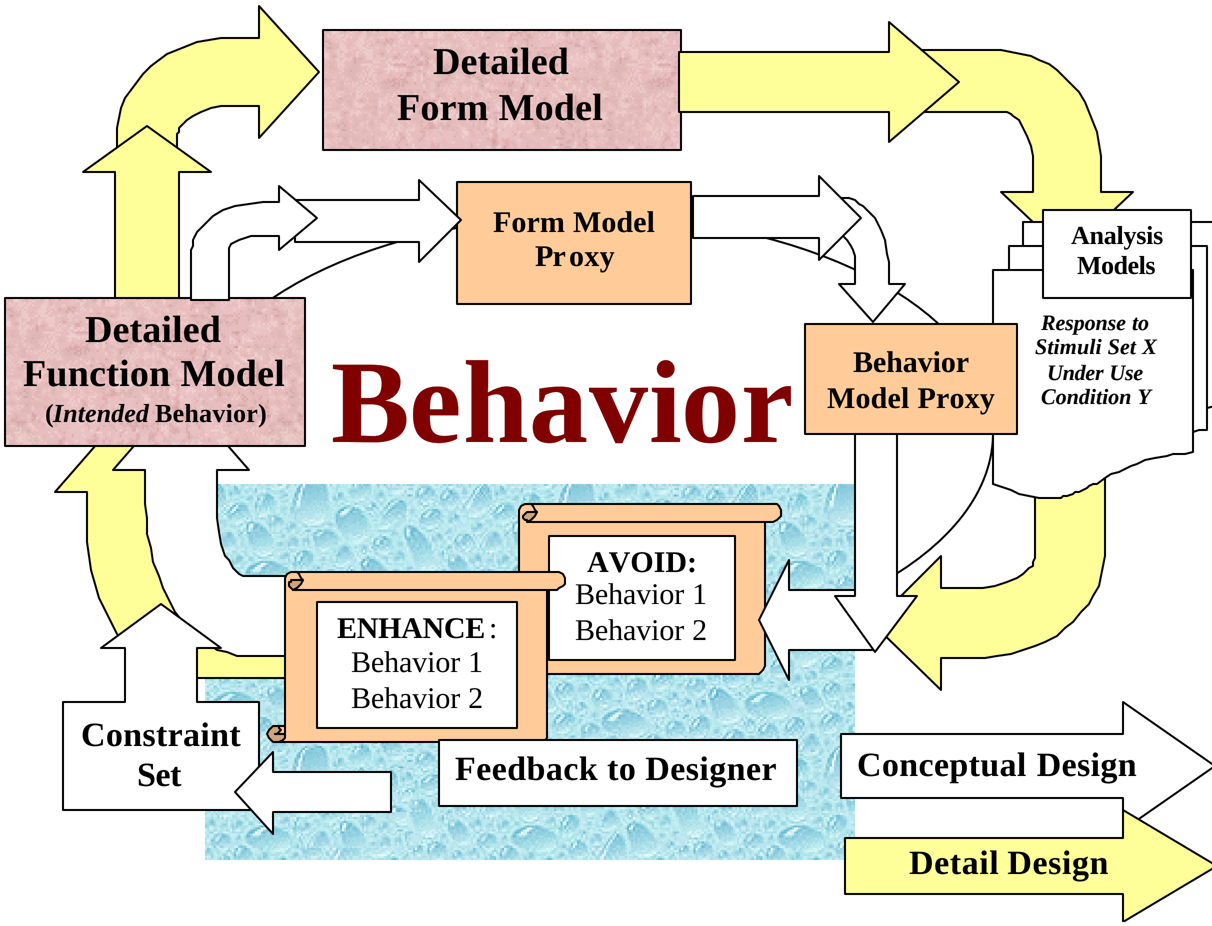

Figure 4 - Diagram of the design process emphasizing the role of form, function, and behavior

artifacts that will resolve issues of inadequacy associated with present systems. Should an FFB system become a reality, Figure 4 reduces to Figure 5. This figure takes into account the usage of form, function, and behavior-based models to make a more robust and flexible designer assistance tool. Many systems including Szykman (1999) have left room for behavior-based expansion to complete the device modeling in their representations.

A more complete representation system will also increase knowledge sharing. One of the constraints is that many representations are domain-specific. For example, Shi and Schmidt (1999) have generated a design representation of Meccano set carts, but that system is only useful to carts. Messac and Chen (1999) call for a solidification effort to design representations and a step in that direction involves reducing the amount of domain specificity in systems. FFB, because of its flexible nature, can help reduce the incommunicative nature of today's systems.

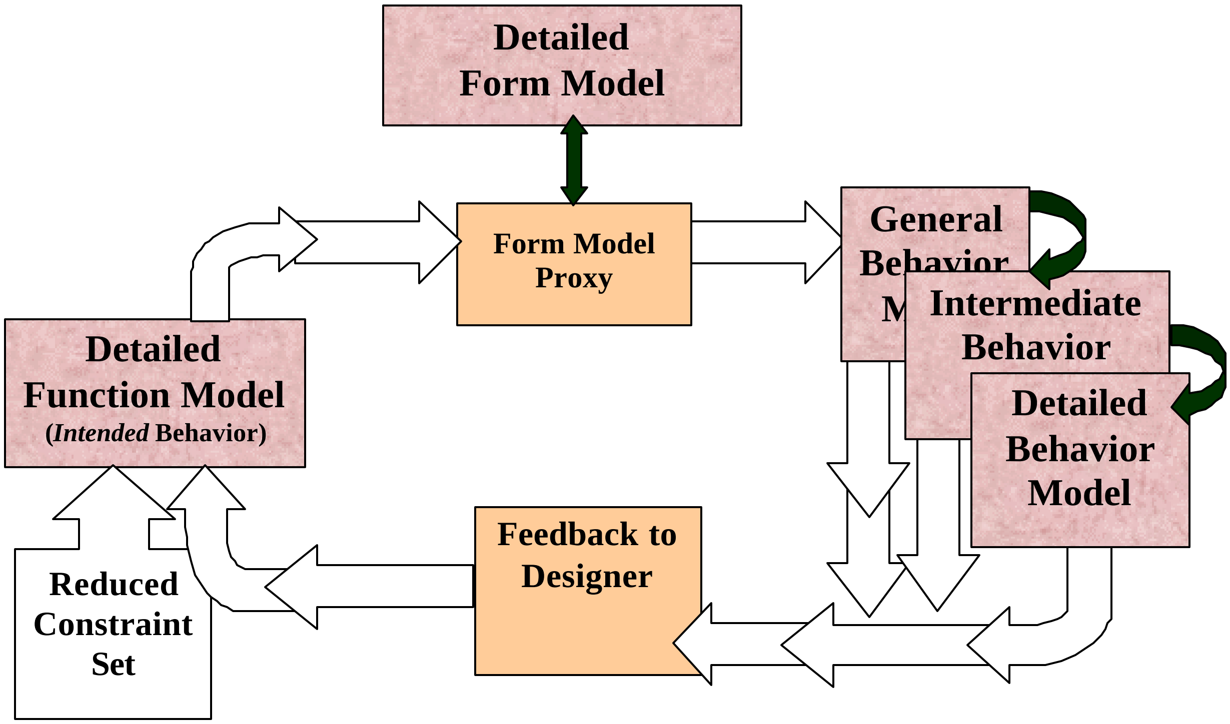

Figure 5 - Modified Design Process

5 Conclusion and proposed future work

Form, function, and behavior views are all necessary for a useful design representation system. Through theoretical and empirical examples, it is shown that form, function, and behavior-based views are problematic during different stages of design and that an integration of all views will alleviate those issues. The integration of the three types of representation views is dependent upon developing a behavior-based representation system to the maturity level of form and function based systems.

After development, an FFB system can assist in such design support tasks as information sharing and information tracking. An effort in this area is the NIST Design Repository Project (Szykman 1998). The design repository acts as a library of designs so that designers can use the knowledge of what has previously been studied to better coordinate their present design plans. The continued work on this project would be supported by efforts into behavior-based systems.

6 References

Ahmed, Seema, Lucienne Blessing, and Ken Wallace, 1999. *The Relationships Between Data, Information and Knowledge Based on a Preliminary Study of Engineering Designers*, Proceedings of the 1999 ASME Design Theory and Methodology Conference, DETC99/DTM-8754, Las Vegas, Nevada.

Altschuller, G., 1984. Creativity as an Exact Science. Gordon and Branch Publishers, New York.

Bogoni, Luca, 1998. "*More Than Just Shape: A Representation for Functionality*", Artificial Intelligence in Engineering, Vol. 12, pp. 337-354.

Callahan, Sean and Jeff Heisserman, 19??. *A Product Representation Support Process Automation*, [Author's note: Reference under investigation]

Chakrabarti, Amaresh and Thomas P. Bligh, 1994. *An Approach to Functional Synthesis of Solutions in Mechanical Coneptual Design. Part I: Introduction and Knowledge Representation*, Research in Engineering Design, Vol. 6, pp. 127-141.

Clausing, Don, 1994. Total Quality Development. ASME Press, New York.

Cowan, F. S., Allen, J. K., Mistree, F., 1999. *Modeling Perspectives with Living Systems Theory in the Design of Complex Engineering Systems*, Proceedings of the 43rd Annual Conference of the International Society for the Systems Sciences, (Allen, J. K., Hall, M. L. W., and Wilby, J., eds.), ISSS, June 27 - July 2, Pacific Grove, California, Paper No. 99037.

Finger, Susan and John R. Dixon, 1989[1]. *A Review of Research in Mechanical Engineering Design. Part I: Descriptive, Prescriptive, and Computer-Based Models of Design Processes*, Research in Engineering Design, Vol. 1, pp. 51-67.

Finger, Susan and John R. Dixon, 1989[2]. *A Review of Research in Mechanical Engineering Design. Part II: Representations, Analysis, and Design for the Life Cycle*, Research in Engineering Design, Vol. 1, pp. 121-137.

Hundal, Mahendra S., 1997. Systematic Mechanical Designing: A Cost and Management Perspective. ASME Press, New York.

Karnopp, Dean and Ronald Rosenberg, 1975. System Dynamics: A Unified Approach. John Wiley & Sons, Inc.

Lowe, Alistair, McMahon, Chris, Shah, Tulan, and Culley, Steve, 1999. *A Method for the Study of Information use Profiles For Design Engineers*, Proceedings of the 1999 ASME Design Theory and Methodology Conference, DETC99/DTM-8753, Las Vegas, Nevada.

Pahl, G. and W. Beitz, 1977. Engineering Design, A Systematic Approach, First Edition. Springer-Verlag, London.

Pahl, G. and W. Beitz, 1996. Engineering Design, A Systematic Approach, Second Edition. Springer-Verlag, London.

Petrovski, Henry, 1992. To Engineer Is human: The Role of Failure in Successful Design. Vintage Books, New York.

Stone, Robert B. and Kristin L. Wood, 1999. *Development of a Functional Basis for Design*, Proceedings of the 1999 ASME Design Theory and Methodology Conference, DETC99/DTM-8765, Las Vegas, Nevada.

Szykman, Simon, 1998. *The NIST Design Repository Project*. <http://www.mel.nist.gov/msidstaff/szykman/private/KP-1.html>, 22 June 1998.

Szykman, Simon, 1999. The Representation of Function in Computer-based Design. (Contact corresponding author for information.)

Thompson, Brian, 1998. Creative Engineering Design, Fourth Edition. Okemos Press, Okemos, Michigan.

Ullman, David G., 1993. "*The Evolution of Function and Behavior During Mechanical Design*", Design Theory and Methodology, Vol. 53, pp. 91-103.

Ullman, David G., 1997. The Mechanical Design Process, Second Edition. The McGraw-Hill Companies, Inc, New York.

Ulrich, Karl T. and Steven D. Eppinger, 1995. Product Design and Development. McGraw-Hill, Inc., New York.

Umeda, Y., H. Takeda, T. Tomiyama, and H. Yoshikawa, 1990. *"Function, Behavior, and Structure,"* Applications of Artificial Intelligence in Engineering V, Ed. Gero, Proceedings of the Fifth International Conference, Boston, Massachusetts.

Zhang, GuangMing, 1999. Engineering Design and Pro/ENGINEER, Second Edition. College House Enterprises, LLC, Knoxville, Tennessee.