

# A REPRESENTATION OF CARRIER FLOWS FOR FUNCTIONAL DESIGN

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## ABSTRACT

This research investigates and establishes a convention for the functional representation of the primary/carrier flow relationship utilizing the Functional Basis for design. Through primary and carrier flows, a designer can focus a functional model to specifically represent an individual aspect of an electromechanical system. Inclusion of carrier flows in functional modeling also allows designers to capture the flow functionality of simply transporting another flow through a system. Adding a carrier flow convention will allow a product designer to properly represent the primary/carrier flow relationship within a product, and thus the designer will be better able to accurately store, access, and utilize functional models as a design tool. In this work, carrier flows are described and demonstrated in a specific electromechanical example to show how they can be applied to a functional model to illustrate a specific design focus. The same product is then shown with respect to the repository entry application to demonstrate how the design information can be stored for future access and utilization.

*Keywords: Function representation, functional modeling, functional focus, design modeling, systems modeling, primary/carrier flows.*

## 1 INTRODUCTION

Over the course of several years of research and integrated design coursework at the University of Missouri–Rolla (UMR), a body of product design knowledge has been developed for over one hundred consumer products. This body of product design knowledge includes functional models, assembly models, bills of materials (BOM), design structure matrices (DSM), function-component matrices (FCM), and artifact images. More recently this body of knowledge has been transformed to a digital representation that resides within a design repository housed at UMR. Through the utilization of functional models and the established repository framework, additional and more complex products continue to be decomposed and archived at increasing levels of resolution. As the scope of product decomposition increases, it becomes imperative to establish additional modeling formalisms through increased representation within a design repository, more stringent modeling guidelines, and more representative modeling practices.

Frequently during product design, representation or archival it becomes apparent that a flow's primary purpose is to *carry* or *transport* another flow through the system [1]. This paper introduces the concept of a primary/carrier flow relationship and its application in traditional functional modeling techniques [2]. Guidelines for the representation for carrier flows are provided, and the carrier flow representation is demonstrated for product design and design knowledge storage with an online repository database. The carrier flow representation is then applied to a computer mouse system to show its application for the representation of design perspectives and carrier flow information in a functional model.

## 2 BACKGROUND

### 2.1 The Functional Basis

The Functional Basis in its current form is best described as a taxonomy of function (verb) and flow (noun) terms for prescribing functionality during early product design and is a refinement of past ideas with the intent to model systems functionally. With Miles [3] and Rodenaker [4], the first instances of using verb-noun pairs and input-output flow transformations for function representation are

researched. Miles developed functional representation on the premise that any product is useful because of the product's inherent functionality. Rodenacker used descriptions of material, energy or information along with an input-output transformation to represent functionality. From these early representations of functions, many researchers have continued work to effectively and accurately describe functionality. Pahl and Beitz present the idea of a functional basis for product decomposition with material, energy and signal flows [5], and Hundal presents a further refined set of function and flow classes [6]. This work, however, lacks a separate function category for signals. The research is further refined by Little, *et al.* with the functional basis set [7].

Addressing the need for a clear vocabulary to describe product function, the Functional Basis has emerged as a standardized design lexicon [8]. It was formulated in conjunction with NIST to unify two similar, independent research efforts [9], [10]. The Functional Basis consists of two sets of morphemes: one containing action verbs to describe function and a second containing nouns to describe flow. The Functional Basis spans all engineering domains while retaining independence of terms. The function set of the Functional Basis is broken down into eight categories termed the primary classes. These classes have further divisions at secondary and tertiary levels that offer increasing degrees of specialization. The primary class represents the broadest definition of distinct function while the tertiary class provides a very specific description of function. The secondary level of the function set, containing twenty-one action verbs, is the most often used class of the Functional Basis. The primary class and secondary function terms are shown in Table 1.

*Table 1: Function classes and their basic categorizations*

Primary	Branch	Channel	Connect	Control Magnitude	Convert	Provision	Signal	Support
Secondary	Separate	Import	Couple	Actuate	Convert	Store	Sense	Stabilize
	Distribute	Export	Mix	Regulate		Supply	Indicate	Secure
		Transfer		Change			Process	Position
		Guide		Stop				

The flow set of the Functional Basis allows for the associated function's input and output flows to be described. Similar to the function set, there are three distinct classes within the flow set of the functional lexicon. Within the primary class of the flow set, there are three main categories used to describe flow: material, signal and energy, as popularized by Pahl and Beitz [5]. Each of these categories has the capability to represent the input or output of a function. The secondary class of this set has 20 nouns that are used to describe the type of flow. Again, it is the secondary class of the Functional Basis that is primarily used when describing a product. The primary class and secondary flow terms are shown in Table 2. The tertiary level is omitted from Tables 1 and 2 for reasons of brevity, and can be found in [8].

*Table 2 – Flow classes and their basic categorizations*

Primary	Material	Signal	Energy		
Secondary	Human	Status	Human	Electrical	Mechanical
	Gas	Control	Acoustic	Electromagnetic	Pneumatic
	Liquid		Biological	Hydraulic	Radioactive
	Solid		Chemical	Magnetic	Thermal
	Plasma				
	Mixture				

## 2.2 Functional Modeling

A functional model is a description of a product in terms of the elementary functions and flows that are required to achieve the product's overall function or purpose. A graphical form of a functional model is represented by a collection of sub-functions connected by the flows on which they operate [10]. This structure is an easy way for a designer to see what type of functions are performed without being distracted by any particular form the artifact may take.

Using the Functional Basis to represent product functionality within the design repository allows product knowledge to be stored, categorized and searched by their function. This abstraction allows the designer to focus on overall functionality and to develop more creative solutions for solving a design problem [11].

### 2.3 Design Repositories

Several researchers, institutions and corporations have developed systems to capture product functionality on some level. The captured functionality ranges from detailed function and behavior information to loose hierarchical artifact relationship views. Functional representations have been used to represent design knowledge in early repository systems. These systems used a block diagram approach and were based on “function logic.” One of these early systems, described by Sturges [12] and powered by Hypercard stacks, was used to navigate function diagrams. The representation schema used by Sturges built on function logic to describe complex systems and included mathematical relationship equations in relationship to the “function blocks.” Through the use of “function logic” and “function blocks” designers were able to gain insight on how a product operates functionally.

In hopes of providing guidance to product representation research, NIST (National Institute of Standards and Technology) has developed a set of information models to be used for modeling product knowledge at varying levels of detail. There are several data entities allowing for a variety of aspects of a product description to be represented. The classes specified in the NIST Core Product Model include: Artifact, Function, Transfer Function, Flow, Form, Geometry, Material, Behavior, Specification, Configuration, Relationship, Requirement, Reference and Constraint [13]. Along with these classes there is a set of specific information needed with each item and a specified type of value that can be entered.

Building on the Core Product Model specified by NIST, researchers at UMR have implemented a fully functional and populated design repository system [14]. The design repository at UMR makes use of a relational database to store product information, java server pages (jsp) for product information display and search over the Internet, and a C++ based GUI application for product entry. The UMR design repository project is an artifact-centric repository, meaning that for a design attribute to exist, it must be linked to an artifact. Design information types contained in the repository such as functionality, parent artifact, failure, manufacturing and physical parameters, describe additional design attributes while still relating to their artifact hub. The main interface of the design repository can be found at <http://function.basiceng.umn.edu/repository/>.

## 3 MOTIVATION AND METHODOLOGY

The functional decomposition of electromechanical products for data entry within the Design Repository [14] has revealed a frequent trend where flows do not work explicitly to complete the black box functionality of a product; however, they are the carrier of a flow fundamental to the completion of the black box functionality. When a designer recognizes such a flow, he or she is presented with two options 1.) include the flow in the model, or 2.) disregard the flow completely. If the designer chooses the first option, how can it be recorded in a manner that reflects whether the flow in question is fundamental to the completion of the black box functionality or if it just merely exists? If the designer chooses the second option, they run the risk of degrading model integrity, which is highly important in cases where the model is archived within a design repository and used for concept generation activities.

Take for example the model of a simple residential light switch. The importing of a control signal to toggle the flow electrical energy would require three distinct flows: human material, human energy, and an on/off control signal. Each of these three flows could be modeled independently as three distinct function chains or they could be modeled as one or two distinct function chains utilizing primary/carrier flows. Depending on the viewpoint of the designer or product archivist, the functional model could be constructed with the on/off control signal as the primary flow and with human material and energy as the carrier flows, or the functional model could be constructed such that the human material flow was the primary flow with human energy and a control signal as carrier flows. Or, a designer might choose to model both the on/off control signal and the human material as primary flows each with carrier flows of human energy. The functional modeling direction that a designer or archivist takes depends on what aspect of the light switch the designer is trying to capture. The question then becomes, how does the designer represent and archive the carrier flow information in the model?

A careful study of the products housed in the repository reveals that many of the design students and archivists who have entered products into the repository have faced the question posed by the light switch of how to represent and archive carrier flow information. Noticeable within the repository and

during design knowledge entry, several artifacts had at least two of the same functions but were operating upon different flows. From a designer or archivist perspective, it can be obvious which flow should pair with a given artifact. But from a computational perspective, there is no differentiation. Thus, future designers using the repository could inaccurately understand design information documented in such a fashion. Designers using the automated morphological matrix or concept generators would be returned erroneous results thus limiting the usefulness of the Design Repository. To relieve ambiguity brought about by multiple flow types passing through a single function, *primary* and *carrier* classes were implemented within the repository data schema. The *primary* and *carrier* descriptors were first used only to test data integrity within the repository and related concept generation activities.

To further test the convention for functionally representing the primary/carrier flow relationship, electromechanical products that were decomposed, modeled functionally, and stored in the design repository were investigated for the presence of carrier flows. Specific attention was given to the modeling of individual components with more than one flow type since these seemed most likely to have an inherent carrier flow due to their ability to perform function on more than one flow. Also, attention was provided to flows in functional models that could not be aggregated with the entire system. Through this study it was found that the primary/carrier flow designation not only integrated well within the repository data schema but also within the realm of functional modeling techniques.

## **4 RESULTS**

### **4.1 Applying carrier flows to a functional model**

Primary/carrier flow properties allow the designer to represent a primary flow required to meet the input/output requirements of the black box model, and its supporting carrier flow that aids the primary flow in the completion of its black box requirements. Adhering to standard modeling techniques material, energy and signal flow can be designated as either a primary or carrier flow. A primary flow, being of functional significance to the system as a whole, is described by each function block that it passes through. For convention, when functionally modeling primary/carrier flows, the primary flow is drawn entering a function block above carrier flows, or it is drawn to the right of carrier flows for a direction change downward and to the left of carrier flows with a direction change upward.

Primary/carrier flow properties are typically consistent across function chains; however, there are times when it may be necessary to represent changed functionality of a flow that in a prior block was represented as a carrier. Typically, this occurs when the carrier flow changes its form. Due to this ability for a primary/carrier flow property to change, it can be said that primary/carrier flow properties are function chain independent.

### **4.2 Carrier flows and the repository**

Investigating the UMR design repository has revealed numerous products with an obvious potential for the application of primary/carrier flows. For instance, as an example, five vacuum products including one shop vacuum, two hand-held vacuums, one blower vacuum, and one bug collection vacuum that have been entered into the repository use air propelled by pneumatic energy to carry collected dirt into some form of storage reservoir. Also, there are numerous products in the repository that have some type of switch or button for user input. For example, a portable compact disk player uses electrical energy to carry control signals like play/pause, stop, and track forward/backward. As final example, consider all products which use a battery to provide electrical energy to the system. The repository currently includes 40 products that utilize a battery for power. Each of these products must import the solid material battery into the system even though the battery is not directly vital to the black box functionality of the system. Instead, it is the ability of the battery to provide electrical energy to the system that most accurately completes the black box functionality.

The current UMR Design Repository allows for the primary/carrier flow designation, however most entries do not contain primary/carrier flow information. The first step to having primary/carrier flow information available from the repository is add the ability to digitize this information for storage on a local drive or uploading onto a repository. To that end, the newest version of the repository entry application, provided in Figure 1, has been created with the capacity to capture carrier flow information. When an artifact is entered into the entry application, a single sub-function is selected; however, multiple flows can be selected to pass through a function block. When a function exists with

more than one flow, the designer is prompted by the entry application to select either primary or carrier flow type. Each function block should only have one primary flow, thus all other flows passing through the function block are selected as carrier in the appropriate *Carrier* column. In Figure 1, a sample system utilizing carrier flows has been entered into the entry application using the vacuum system as a basis. The solid flow (dirt) is carried by pneumatic energy and air material, thus pneumatic energy and air material are denoted as carrier flows.

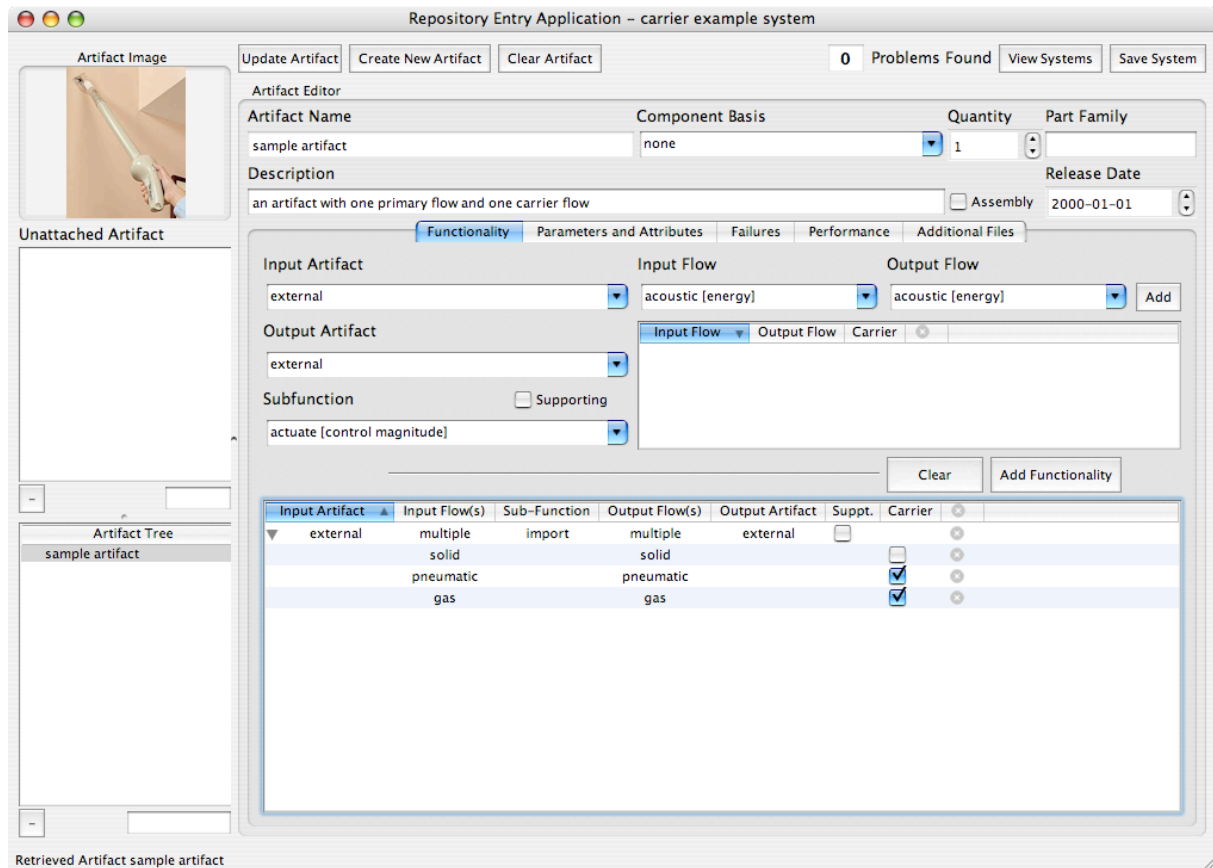


Figure 1: Screenshot of the UMR Design Repository entry application

Within the UMR Design Repository each function has been allowed multiple flows without the need to repeat function. Previously, multiple flows were allowed to pass through a function without the designation of a single primary or *important* flow. While such a scheme did record design knowledge, the knowledge was not fully describing the intricacies of artifact functionality.

## 5 APPLICATION

To demonstrate the primary/carrier flow relationship for functional models, a computer mouse has been disassembled, modeled functionally, and entered into the UMR design repository. The computer mouse can be thought of from two differing design perspectives: as a computer controller and from an ergonomic standpoint. These models can be aggregated to provide a complete model as would be typically entered into the UMR design repository, and will be shown as such with a screen shot from the entry application.

The design focus of the computer mouse can change the perspective from which a functional model is developed. With primary/carrier flows, a designer can essentially shift focus away from information that is beyond the focus of the current design. For instance, with the computer mouse, the design could focus on the computer mouse as an intermediary to convey a signal between the user and the computer, which would require control signal primary flows through the functional model. However, if the computer mouse were being designed from an ergonomic perspective, then the material flow interactions between the human and the intermediary (mouse surface) would be the primary flows. Human material modeled as a primary flow would ensure that designers take as a key concern the interaction of the device with the human body. From both perspectives, the black box

functionality and the flows through the computer mouse would be the same. The black box functionality of the computer mouse would be *transfer control signal*. The flows for the computer mouse would be human material and energy for reactions, electrical energy from the computer, and a control signal to indicate the desired computer reaction. The outputs from the black box would also be the same, the computer mouse would export signal and electrical energy to the computer; an auditory signal would indicate the reception of the control signal, and the human material and energy would in some way leave the system. The black box model in Figure 2 shows these flows.

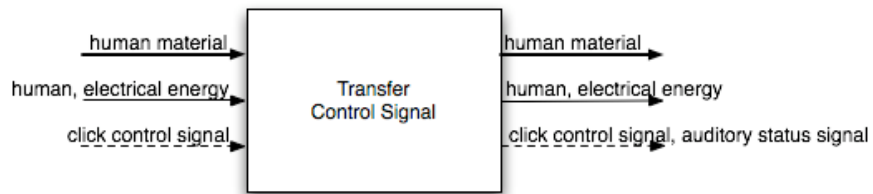


Figure 2: Computer mouse black box functionality

To show how primary/carrier flows can be utilized to illustrate a design focus, the computer mouse has been modeled following the two previously discussed modeling foci: as a human-computer control intermediary and for human-material ergonomic standpoint.

Modeling the computer mouse from the control signal aspect requires that signal flows be of primary functional focus as illustrated in Figure 3. The control signal *click* must be imported into the system as a primary flow with human material and energy entering the system as its carrier flows. As per primary/carrier flow notation, the primary flow, *control signal*, is drawn above its carrier flows, *human energy* and *human material*. The function labeled on each functional block acts on the primary flow. Following signal grammars, the *click* control signal is transferred to an *actuate electrical energy* function block to initiate the flow of electrical energy back to the computer. After the *actuate electrical energy*, human energy and material cease to carry the control signal, and instead, the control signal is carried by electrical energy to the computer.

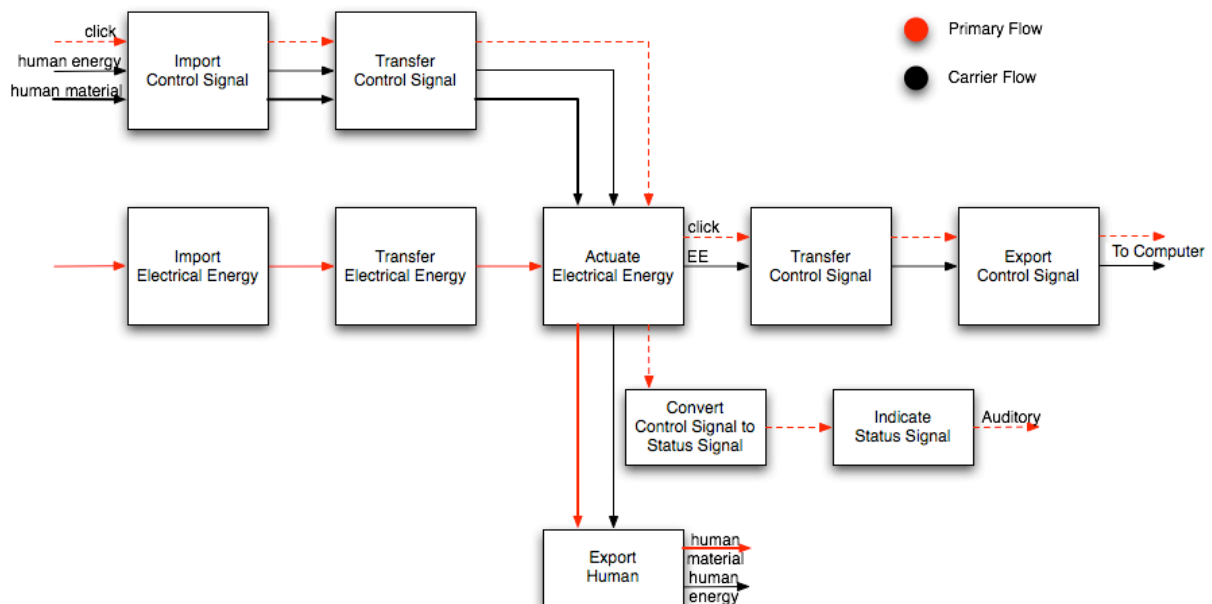


Figure 3: Signal flows as the functional focus

For a design focusing more on the ergonomic standpoint of the computer mouse, a designer might choose to illustrate only the material interaction aspect of the computer mouse. Figure 4 provides a functional model with material flows as the functional focus. A functional model with material focus imports human material as the primary flow with carriers of human energy for motive ability and control signal for direction. The human material is guided and positioned before being

sensed by the mouse. Upon sensing of the mouse, status can be indicated and a control signal can be sent as a primary flow carried by electrical energy to the computer.

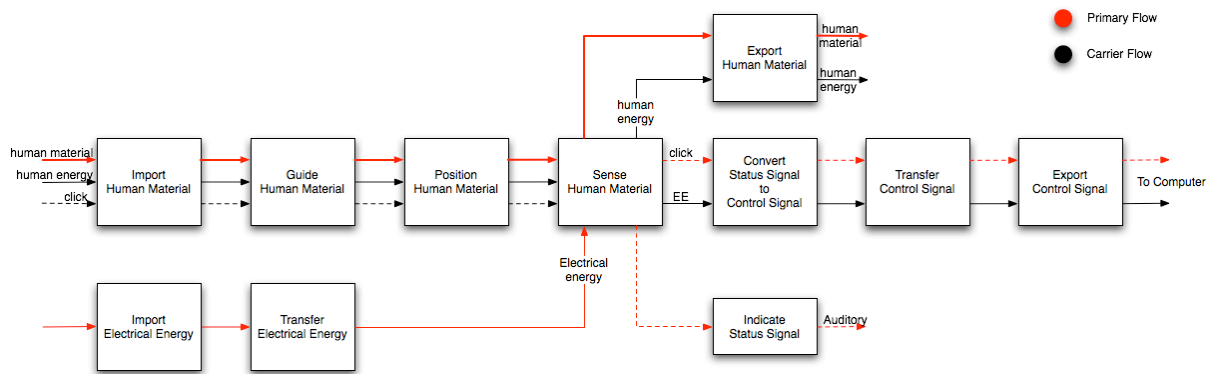


Figure 4: Material flows as the functional focus

Entry of the computer mouse into the UMR design repository requires a more complete functional model representing the entire functionality of the computer mouse, which would simply be an aggregation of both the material flow focused and the signal flow focused functional models. The complete aggregated functional model still adheres to the original black box functional model provided as Figure 2 with human based material, energy and control signal flows and electrical energy entering the computer mouse system. The computer mouse system performs the black box functionality to transfer a control signal from the human user to the computer, and thus, exports a control signal from its system to the computer. Provided in Figure 5 is the complete functional model of the computer mouse utilizing the primary and carrier flows.

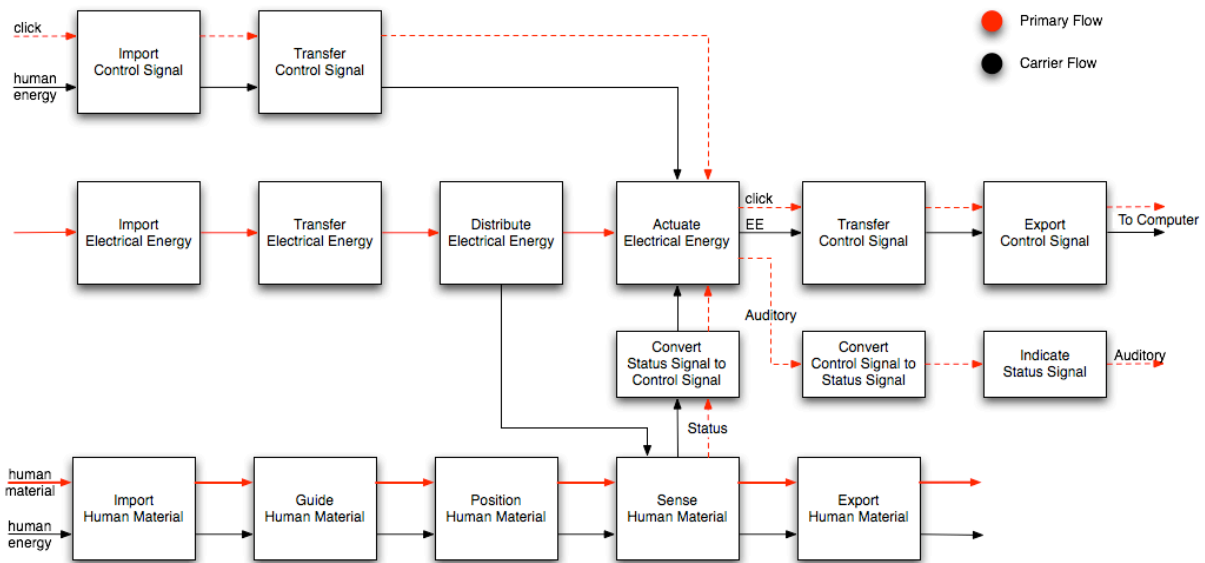


Figure 5: Aggregated functional model of a computer mouse

The aggregated computer mouse functional model shows the direct relationship between the *click* control signal and the human material. Both the control signal and the human material enter the computer mouse system as primary flows carried by human energy, and are used together to actuate the flow of electrical energy. Once the flow of electrical energy is activated, the electrical energy switches from the primary flow to the carrier flow that carries the *click* control signal. The control signal is then exported to the computer.

Utilization of primary/carrier flows in the aggregated functional model allows for the human energy flow to be correctly modeled and stored with the functionality of carrying primary flows through the system. Before the use of carrier flows, the human energy flows would have either been disregarded or simply passed through the system in a non-aggregated function chain that completely misrepresents the flow of human energy through the system. However, being able to model the

primary/carrier flow relationship within a product design does not completely utilize functional modeling as a design tool. Primary/carrier flows must be compatible with data storage and access and reuse. To that end, primary/carrier flows have been included in the UMR design repository and the product entry application to allow for their capture during product dissection and archival and to allow for the information to be accessed at a later date from the repository.

The screenshot in Figure 6 of the repository entry application focuses on the top cover of the computer mouse. The top cover of the computer mouse imports the initial human flows (control signal, material, and energy) that are eventually manipulated to command some operation from the computer. In the upper left hand corner of the screenshot, the image of the top cover of the mouse is shown with the artifact name to its right. The lower right hand field is where the functionality assigned to the top cover is displayed back to the user. The flows associated with the import function corresponding to the top cover artifact have already been entered into the application to correspond to the computer mouse functional model provided in Figure 6. The flows being imported by the top cover artifact are human energy, human material, and control signal. The imported flows are all external *input artifacts* since they are first brought into the computer mouse system by the top cover artifact. The function display field works similarly to the function blocks in the functional model, where the flows entering the function block are listed as *input flows* and the flows leaving the function block are listed as *output flows*. Import is the *sub-function*. The destination or *output artifact* of all of the flows remain within the top cover, and further functions such as transfer and guide are performed by the top cover before the flows will enter another artifact. These additional functions performed by the top cover would require entry to complete the artifact representation. The human energy flow is designated as being a carrier flow by the checkmark in the *carrier* column.

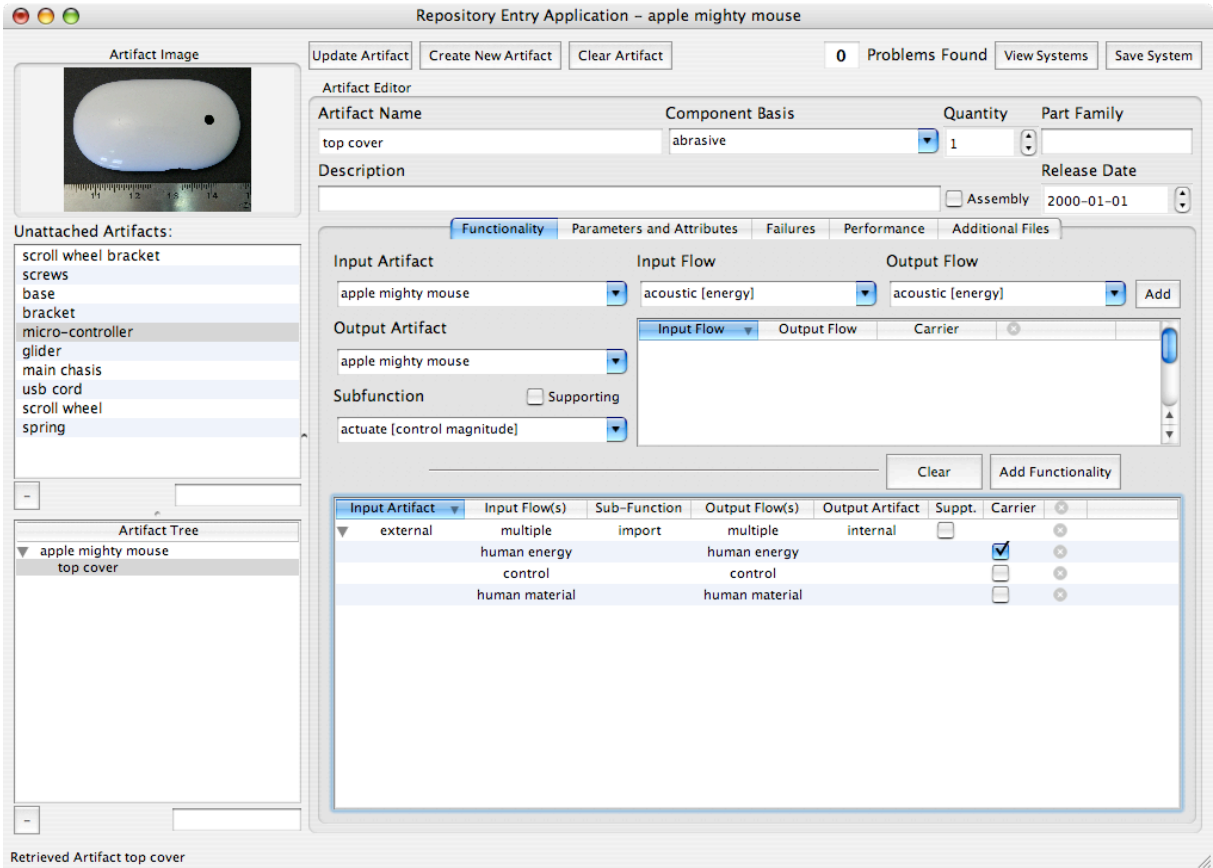


Figure 6: Repository entry application screenshot of a computer mouse

The representation within the repository entry application can then be saved to a local machine or uploaded to the UMR design repository. From the UMR design repository, the design information can be accessed around the world providing component functionality and parameter statistics, which can be used to aid early design decisions based on stored prior design information.



## 6 CONCLUSIONS

This research provides a convention for the functional representation of carrier flows using the Functional Basis for design without drastically altering current modeling practices. The addition of primary/carrier flow designations has helped to further formalize functional modeling techniques. Designers can now rigorously focus a functional model to capture specific design aspects, and yet still maintain the accuracy of a functional model by capturing all product flows. Also, important yet sometimes disregarded flows that before could not be aggregated into the overall functional model can now be incorporated and modeled in a way that accurately represents their true functional nature as a carrier flow. The integration of primary/carrier flow distinctions in to the repository data schema and related software components, allow carrier flows to be fully utilized as a design tool. The inclusion of carrier flows in the UMR design repository and its associated entry application allows for their capture and archival during product dissection, so they can thus be accessed at a later date from the repository.

Future work of the carrier flow representation will include its utilization in product design and archival purposes. Product dissection and archival continues to test the limitations of functional modeling, the Functional Basis, and the Design Repository as design students decompose, model functionally, and archive new products from varying engineering domains. The primary/carrier flow relationship, now fully implemented, will be tested alongside all other design tools at UMR.

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