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SIGNAL FLOW GRAMMAR FROM THE FUNCTIONAL BASIS

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ABSTRACT
This research establishes grammar built from the Functional Basis to standardize the usage of signal flows in the functional modeling of electromechanical products. This is part of a larger effort to transform the Functional Basis, currently a structured set of terms describing product functionality, into a formal language – Functional Basis Modeling Language (FBML). When used properly, the Functional Basis inherently establishes structure defining how function and flow should be used in design of electromechanical products. However, established structure can often be debated and requires the morphology and syntax of a rigid grammar to provide for consistent application. This research aims to move the Functional Basis toward a functional modeling language, FBML, and to clarify signal flow usage through grammar consisting of morphology and syntax to provide more consistent modeling of the sensory elements vital to electromechanical design.

Keywords: Functional models, functional basis, signal flows, taxonomy, grammar, syntax, morphemes, morphology.

1 INTRODUCTION
Electromechanical design often requires designers to create an engineering solution spanning multiple engineering domains. Often this forces engineers to synergistically consider design elements across numerous engineering domains such as mechanical, electrical and computer. For successful products to emerge, integration of all engineering domains must be considered through all phases of product design. Design elements must communicate and work together flawlessly, thus requiring adequate communication, monitoring, processing, and decision-making abilities. Information, *i.e.* signal flow, is vital for accurate modeling of these abilities. During conceptual design, functional modeling with the Functional Basis provides the graphical and semantic tools required to develop a complete model; however, the Functional Basis does not explicitly establish grammar consisting of morphology and syntax for its usage. Having a language without grammar makes it difficult for designers to work together to develop uniform and synergistic models that completely and accurately represent all engineering domains.

This paper describes the start of an evolution toward a functional modeling language with a clear morphology, syntax, lexicon, semantics, and graphology. Analogies are drawn between a formal language and functional modeling with the Functional Basis. A clear morphology and syntax for the usage of signal related function and flow terms is presented and applied to an automatically opening garage door.

2 BACKGROUND
The techniques of functional modeling allow a product designer to graphically represent both function and flow in early design and can be found in many texts on engineering design methodologies [1-9]. When functional modeling is performed with the Functional Basis, product designers have at their disposal a taxonomy of function and flow terms where functions take the form of action verbs and flows take the form of nouns [10, 11]. The complete taxonomy of terms provided by the Functional Basis can be found at [11].

In an effort to standardize the assembly of functional models and to shorten the learning curve, Sridharan, *et al.* put forth grammar rules in the form of function structures [12, 13]. The grammar rules are based on products dissected and modeled with the reconciled Functional Basis and are

archived in the University of Missouri-Rolla (UMR) Product Design Repository. The grammar rules are meant to capture all possible flows between function structures. Some problems with their grammar rules include that they are established from trends recognized in the UMR Product Design Repository, thus errors in archived product design information are propagated into their grammar rules. Also, their grammar rules were only established for energy and material flows due to an inherent ambiguity of signal flows that Sridharan, *et al.* attribute to environmental unknowns. Because signal flows were omitted from their grammar set, it becomes difficult to utilize the function set to generate an accurate functional model integrating multiple engineering domains.

What is a signal flow? A signal is typically defined as information about a system or its surroundings. In the text *Product Design*, signal flows are defined as the information for the "internal decision-making capability of a device or sensory data provided to or by a device or process" [7]. Stone, *et al.* when developing the Functional Basis, further define a signal by clarifying it as either a material or energy flow with the specialized purpose of carrying information [10]. In electromechanical design, signals are vital to establish the synergy among engineering domains. Increased recognition of the need for integrated design among engineering disciplines through the acceptance of fields such as mechatronics has increased the need for a clarified methodology to systematically represent system level signal flows in functional models.

At the heart of many mechatronic systems lies a control scheme based on system sensory data, which bonds the system with comprehensive integration. Traditionally, control systems are modeled via a block diagram, where individual blocks represent an element of either the controller or the system and are connected with lines representing the flow of information [14]. Blocks are typically labeled to denote what dynamics they represent and contain a transfer function modeling the dynamic response of the system element. Block diagrams are a useful tool for the designer of the control system but fall short in aiding the overall system design due to a failure to functionally represent all component interactions, whether through signal, energy, or material flows.

In an effort to model control systems at a design level, DeJiu Chen, *et al.* research the functional requirements of control systems giving primary focus to informational flow (either data, control or mixed) and its characteristics as applicable in a control system [15]. The research of Li Chen and Jayarem, *et al.* establishes a functional modeling methodology for mechatronic systems that tries to fill the void in typical control system modeling techniques and bridge the gap between functional modeling of control systems and all other non-controls based product interactions [16, 17]. These methods, however, do not present a methodology to integrate system interactions not requiring direct control into their model.

Rajan, *et al.* apply functional modeling to control systems by developing a four-step methodology for modeling control systems based on the reconciled Functional Basis [18, 19]. Their work looks at the development of the model for the controller and its associated input transducers. Through modeling a wide array of input transducers, Rajan, *et al.* establish a signal modeling methodology to model the transmitted signal and energy flows within each transducer. Their research, however, considers the signal and energy flows separately, not making the connection that energy is the carrier of the signal flow. The models contain knowledge that is useful for product dissection and failure analysis but are far more detailed than can be achieved during the functional stages of conceptual design.

3 METHOD

An analysis was performed on signal flow inconsistencies of 20 electromechanical products dissected and modeled functionally by design students with the terms provided by the Functional Basis. The analysis revealed vastly different modeling techniques and a lack of consistency among student-modeled products. Since each student developed their models from the same modeling terms, there was consistency among the function-flow pairs between students; however, the joining of function-flow blocks lacked consistency and at times was difficult to follow. Frequently, students failed to follow the semantic rules inherently built into the definitions of function and flow terms from the Functional Basis.

To overcome this deficiency, it becomes important to evolve the Functional Basis into a formal modeling language – Functional Basis Modeling Language (FBML). As it exists today, the Functional Basis is best described as a taxonomy with detailed term definitions for the classification of product functionality. A taxonomy is defined as "a scheme of classification," [20] where a scheme is a "large

scale systematic plan or arrangement for attaining some particular object" [20]. The current Functional Basis as a taxonomy of terms for product design is a refinement of past ideas aiming to model systems functionally. Pahl and Beitz first present the idea of a functional taxonomy for product decomposition with material, energy and signal flows and five generally valid functions [6]. Hundal presents a further refined set of function and flow classes [4]; however, this work lacks a separate function category for signals and is further refined by Little, *et al.* with the functional basis set [21]. Stone, *et al*. then present the Functional Basis as a design nomenclature of function and flow terms with precise definitions [10]. The Functional Basis is reconciled into its most current form by Hirtz, *et al.* in 2002 [11].

In order to evolve the Functional Basis into a formal modeling language, it becomes important to answer the question, what is a formal language? Traditionally, a language is "the method of human communication, either spoken or written, consisting of the use of words in a structured and conventional way" [20]. This definition has been expanded, however, to include the realm of computing where a language is defined as "a system of symbols and rules for writing programs or algorithms" [20]. A traditional language for human communication consists of five parts: phonology, morphology, syntax, lexicon, and semantics; however, if the language is written as well as spoken, a sixth part, graphology is added to the language's structure [22]. The components of language as defined by Millward in *A Biography of the English Language* are as follows [22]:

- *"Phonology* is the sounds of a language and the study of these sounds."
- *"Morphology* is the arrangement and relationships of the smallest meaningful units in a language. These minimum units of meaning are called *morphemes."*
- *"Syntax* is the arrangement of words into phrases, clauses, and sentences."
- "The *lexicon* of a language is the list of all the morphemes in the language."
- *"Semantics* is the study of meanings or all meanings expresses by a language."
- *"Graphology* … refers to the systematic representation of language in writing."

Considering both the meaning of a traditional formal language and the Functional Basis as the underpinnings of a language, a functional modeling language can thus be defined as the formalized methodology with which designers can meaningfully communicate abstract system functionality. Following the traditional definition of a language, the functional modeling language consists of five parts: graphology, morphology, syntax, lexicon, and semantics. However, since the functional modeling language is a written language relying on graphical representation instead of spoken words and phrases, graphology has been substituted for phonology as the principle method of communication.

Analogies can be drawn between functional modeling with the Functional Basis and traditional languages. The smallest meaningful units of functional modeling are function and flow terms, and as such, they are the morphemes of the language. The arrangement of function and flow terms into function-flow pairs is the morphology of functional modeling. The Functional Basis lists all the morphemes of functional modeling (functions and flows) and thus is the lexicon of functional modeling. Semantics is the study of the meanings of functions, flows, and their pairs (much of which is found in the definitions), and syntax is the arrangement of function-flow pairs into independent function chains and aggregated functional models. Graphology is the written representation of functional modeling though function blocks and flow arrows to form meaningful functional models.

Grammar is the glue employed to pull together all the different parts of a formal language and to thus provide standardized structure. In formal languages, "words must be combined into larger units, and grammar encompasses the complex set of rules specifying such combination" [23]. Grammar is, "the whole system and structure of a language or of languages in general, usually taken as consisting of syntax and morphology and sometimes also phonology and semantics" [20]. The Functional Basis, while having some inherent guidelines in its morphemes, does not explicitly establish a well-defined grammar. Work has been performed to enumerate an initial functional grammar for both energy and material flows [12, 13]; however, signals have not been clarified in such a way. Through a clear morphology and syntax, the researchers aim to develop a signal usage grammar, which when followed, will provide a recipe for the meaningful joining of signal related function-flow pairs taken from the Functional Basis.

Based on the Functional Basis and its function and flow terms, a signal grammar consisting of morphology and syntax is derived. The developed grammar provides templates to aid in the manual and automatic assembly of functional models and guides the assembly of sub-functions, utilizing nodes to clearly establish the location of system boundaries and the required input and output flows.

4 GRAMMAR RESULTS

4.1 Morphology for signal flows

The following twelve rules have been derived from the definitions provided by the reconciled Functional Basis and constitute the morphology for signal flows for the functional modeling language. The signal morphology is meant to clarify the construction of sub-functions of signal flows in electromechanical products. To aid in the visualization of the syntax, rules 3 through 12 are illustrated in Figure 1.

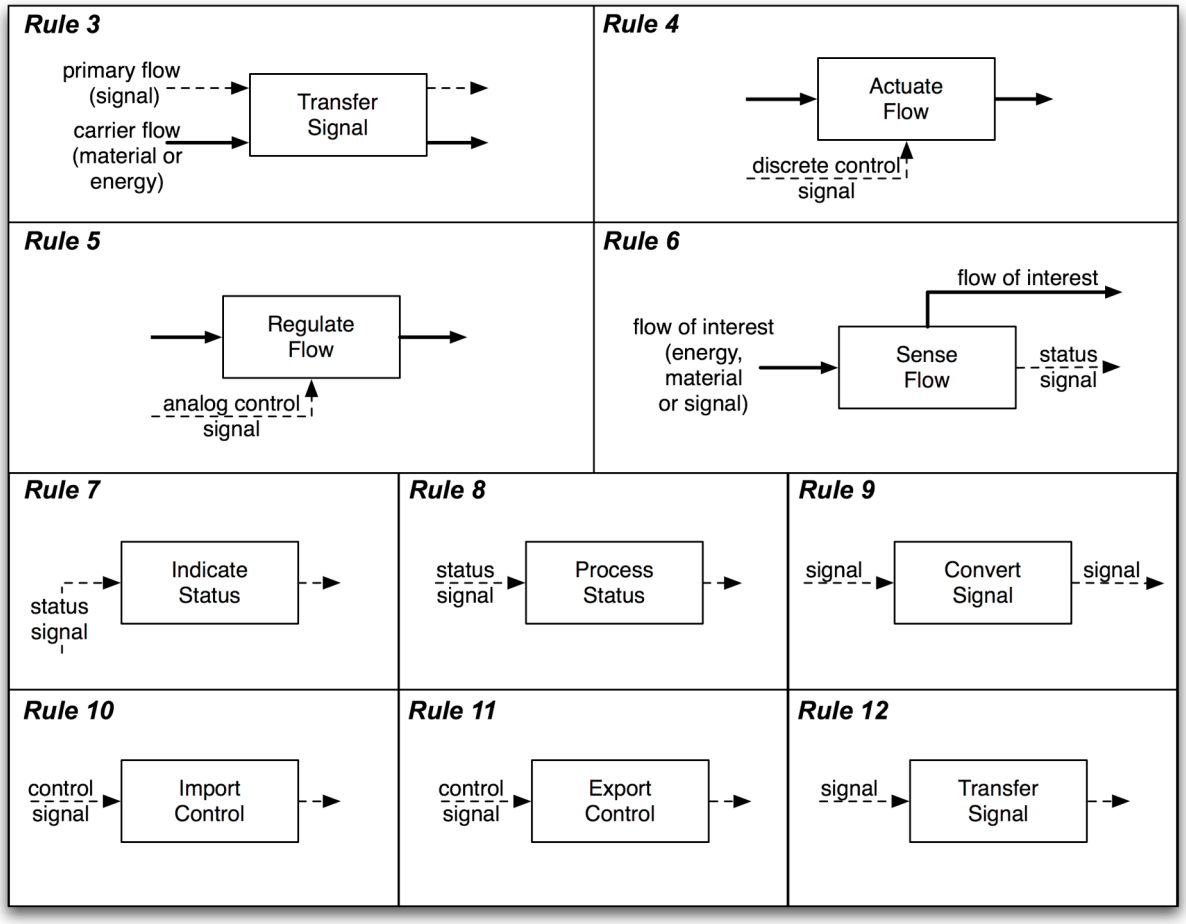

Figure 1. Ten of twelve signal-based rules (primary/carrier, actuate, regulate, sense, indicate, process, import, export and transfer) that have been extracted from the Functional Basis.

1. Use status signals to provide information on auditory, olfactory, tactile, taste, or visual states of the system.
2. Use control signals to send an analog or discrete operational command to an instrument or apparatus.
3. For added detail, use a primary flow to denote a signal and a carrier flow to denote its energy or material carrier.
4. Use the function *actuate* to discretely toggle a flow (*material, signal, energy*).
    - Actuate functions require a discrete control signal to toggle state.
5. Use the function *regulate* to adjust a flow quantity (*material, signal, energy*) in an analog manner.

- Regulate functions require an analog control signal to adjust flow quantity.

6. Use the function *sense* to detect or measure a flow (*material, signal, energy*).
    - Sense functions require an input of the flow of interest to output a status signal representing data collected.
7. Use the function *indicate* to provide system status to the user.
    - Indicate functions end flow paths; thus status flows exiting an indicate function block leave the system and do not connect to other function blocks.
    - Indicate functions do not receive a carrier flow.
8. Use the function *process* to execute a series of operations to extract conditional information on a flow *signal*.
    - Either control or status flows can enter process functions; however, respective entering flows must also exit.
    - To change a status function to a system-usable control signal, a convert function must be implemented.
9. Use the function *convert* to perform the conscience act of changing a signal flows type.
    - A status flow input to the convert function should output as a system-usable control signal, or a control flow input to the convert function should output as a status flow.
10. Use the function *import* to bring a flow *control signal* from outside of the system boundary to the inside of the system boundary.
    - Flow arrows should be drawn into an input function block to represent flow into the system.
11. Use the function *export* to send a flow *signal* outside of the system boundary.
    - Flow arrows should be drawn leaving the export function to represent control flowing from the system.
12. Use the function *transfer* to move a flow *signal* through a system.
    - Either control or status flows can enter transfer functions; however, respective entering flows must also exit.

4.2 Syntax for signal flows

A grammar has been enumerated for both energy and material flows [12, 13]; however, signals, while having inherent Functional Basis guidelines, have no established usage grammar. The previously presented signal flow morphology rules are used to build syntax for signal flows. The syntax rules manifest themselves as functional modeling templates that can be inserted into a functional model, aiding the manual or automatic assembly of functional models, thus increasing the accuracy of product and design representation. Each syntax rule is explained and visually represented in Figure 2. Taken together, the sets of morphology and syntax rules constitute the signal grammar for the functional modeling language.

Actuator: An actuator is a discrete control device used to turn on or off another flow. In conceptual design, if it is known that a flow will be toggled, an actuator should be implemented. To functionally build an actuator, the function term *actuate* must be used in conjunction with rules 3 and 4. A control signal, its carrier, and the flow to be toggled should be imported with *import* function-flow blocks. Then, following rule 12, a *transfer control* function-flow block is applied to route the control signal to an *actuate flow* function-flow block. Optionally the actuator can output its status. To indicate status, rule 9 is followed to convert the control signal to a status signal and rule 7 is followed to indicate the status through a *indicate status* function-flow block.

Regulator: A regulator is an analog control device to adjust a flow in variable manner. When it is known in conceptual design that a flow is to be adjusted in a variable manner, a regulator should be implemented. To functionally build a regulator, the term *regulate* must be used in conjunction with rules 3 and 5. To implement a regulator, a control signal, its carrier, and the flow to be adjusted should be imported with an *import* function-flow block. The control signal and its carrier are routed to the *regulate flow* function-flow block via a *transfer control* function-flow block following rule 12. If the regulator indicates its status, rule 9 is followed to convert the control signal to a status with a *convert control to status* function-flow block, rule 7 is followed to indicate the final status.

Sensor: A sensor is a device used to detect or measure a flow and then output a signal representing collected information. Sensors would be used during conceptual design if a designer realizes that a design must ascertain information about itself or its surroundings. To functionally build

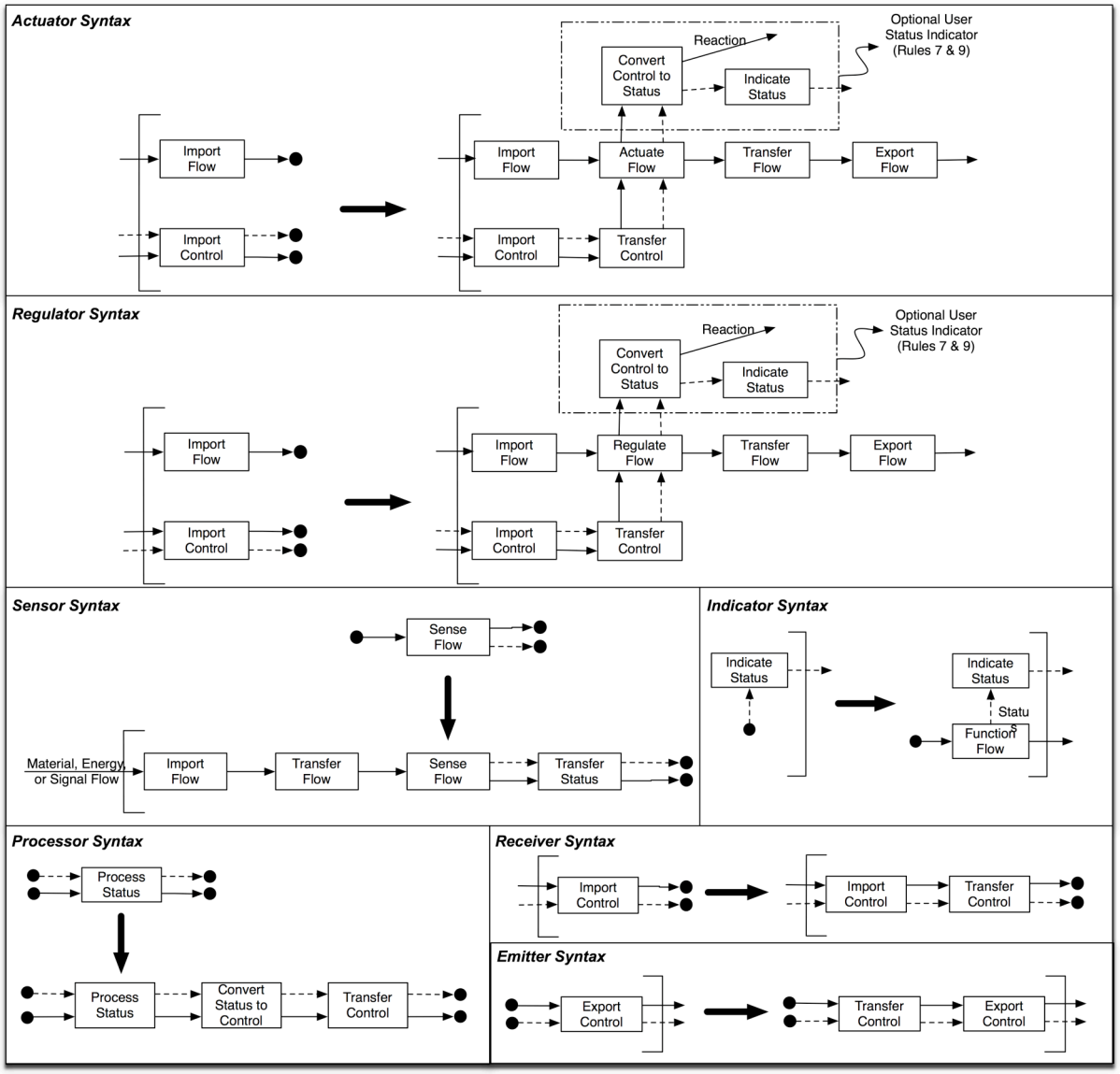

Figure 2. Seven signal-based syntax rules (actuator, regulator, sensor, processor, indicator, receiver, and emitter) have been extracted from the Functional Basis. Black nodes represent connection points, square brackets represent system boundary, and black arrows represent required function/flow insertion.

a sensor, the term *sense* must be used in conjunction with rules 3 and 6. To implement a sensor, transfer a flow (material, energy, or signal) to a *sense flow* function-flow block. The *sense flow* function-flow block outputs primary status flow and its respective carrier flow, which can then be transferred with a *transfer status* function-flow block by rule 12. The final destination of the status flow and carrier can be the system, the user, or both.

The *sense* function can be further detailed at the tertiary level by the reconciled Functional Basis with its tertiary functions *detect* and *measure*. The general sensor functional model can be modified to reflect the increased detail of tertiary terms by using one of the two tertiary terms in place of the *sense* function.

Processor: A processor is any device that analyzes a status signal obtained from a sensor that has ascertained information, either internal or external to the system. Following signal analysis, the processor sends control information to system elements. A processor might be used during conceptual design if a designer knows that the product will need to analyze the state on a series of conditions and make decisions based on the analysis. To functionally build a processor, the term *process* must be used in conjunction with rules 3 and 8. To use a processor, run a primary status flow and a carrier flow into a *process status* function-flow box. Following rule 9, to get a system usable control signal,

connect the *process status* function-flow box to a *convert status to control* function-flow box with another primary status flow and carrier flow pair. Then connect the *convert status to control* to a *transfer control* function-flow box with a primary control signal and carrier flow. By the application of rule 12, the control and its carrier flow is routed via a *transfer control* function-flow box to the controlled system elements.

Indicator: An indicator is any device with the goal of providing vital system information to the user. A designer might use an indicator during conceptual design when it is known that some form of feedback is required from the system. To functionally build an indicator, the term *indicate* must be used in conjunction with rule 7. To implement an indicator, run a status flow from the function-flow block from which system information should be obtained. An indicator is the exception to the primary/carrier rule (rule 3) since it can be as simple as the operation of the system or complex as a series of components providing full diagnostics on system behaviors; in either case, however, an indicator is not required to send the signal outside of the system boundary. An *indicate status* function-flow block ends a flow path (rule 7), thus the status flow that exits an *indicate status* should not enter another function block.

As with the *sense* function, the *indicate* function can be further detailed at the tertiary level by the reconciled Functional Basis with its tertiary functions *track* and *display*. The general indicator functional model can be modified to reflect the increased detail of tertiary terms by using one of the two tertiary terms in place of the *indicate* function.

Receiver: A receiver is used to bring a control signal into the system. To functionally build a receiver, the term *import* must be use in conjunction with rules 3, 10 and 12. To implement a receiver, a new control signal flow and its respective carrier must be imported into the system and thus cross the system boundary. The primary and carrier flows are then routed into the overall system by tying the *import control* function-flow block to a *transfer control* block.

Emitter: An emitter is used to send a control signal from the system. To functionally build an emitter, the term *export* must be used in conjunction with rules 3, 11 and 12. To implement an emitter, run a control signal flow and its carrier flow through a *transfer control* function-flow block. Then tie the control signal and its carrier to an *export control* function-flow block. From the *export control* function-flow block, draw an exiting control signal flow and its carrier to represent them leaving the system boundary.

5 APPLICATION

As an application of the signal usage grammar defining the use of signals and their associated functions, consider an automatic garage door opener. The automatic garage door opener has been modeled following the functional modeling procedure outlined in *Development of a Functional Basis for Design* by Stone, *et al.* [10]. The functional modeling procedure, provided in abbreviated form below, is a three-step method outlining the application of functional modeling techniques to modern product design. The procedure, while intended for the design of a product, still provides a useful set of guidelines for product dissection and reverse engineering [10].

1. Generate black box model
2. Create function chains for each flow
3. Aggregate function chains into a functional model

The first step to developing a functional model is to develop a black box model. At the black box level, the functionality of an automatic garage door opener is to *Open Door*. Inputs include a garage door, human, obstacle, human energy, electrical energy, and wired and wireless on/off control signals.

The second step to generating a sub-functional model is to generate function chains for each input flow. Each sub-function chain should consider the changes and operations that occur to each flow. Considering only the signal input flows, function chains are generated for the obstacle and garage door detection and the wireless and wired on/off control signals. The two function chains developed to detect obstacles and the garage door are solid detectors. The solid detectors, shown in Figure 3, are built by applying the sensor and a processor syntax rules. The sensor rule is required to represent the detection of a solid, and outputs a status indicating the system state into a processor. The

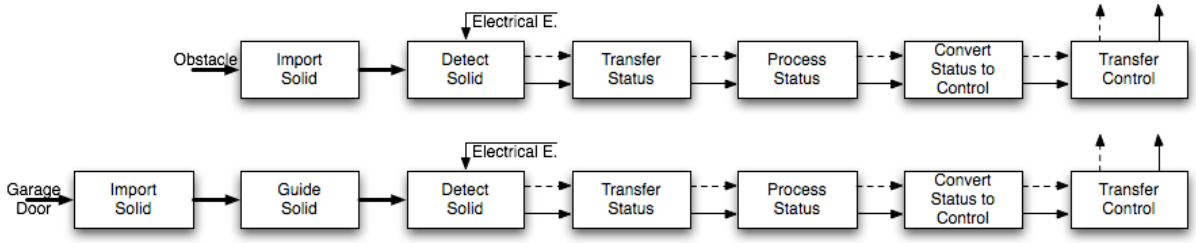

Figure 3. Obstacle and garage door detection function chains

processor determines what to output as a control based on the system status. The wireless and wired on/off switch function chains, shown in Figure 4, are developed following the actuator rule. Both function chains require a control signal carried by the human energy. The control signal is transferred to an *actuate electrical energy* block to turn on or off the garage door opener.

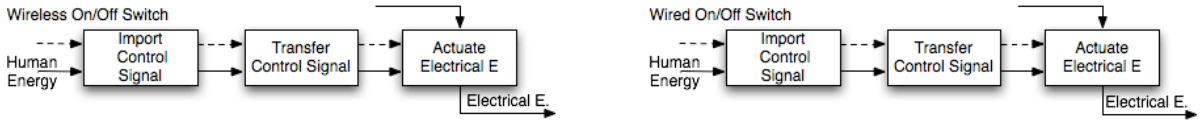

Figure 4. Wireless and wired on/off switch function chains

The third step is to aggregate each of the function chains into an overall functional model of the system, which is provided in Figure 5. The obstacle detector is a safety feature of the garage door, thus its control signal routes into the master *actuate electrical energy* function-flow block controlling the overall operation of the garage door. The garage door detection chain is used to determine when the garage door is up or down and again routes into the master *actuate electrical energy* function-flow block. The wired on/off switch is a master control, and thus routes into the *actuate electrical energy*. Finally, the wireless on/off switch is different: its control signal routes into an *actuate electrical energy* that is part of a separate transmitter that sends a control signal out to the garage door providing a remote actuation feature.

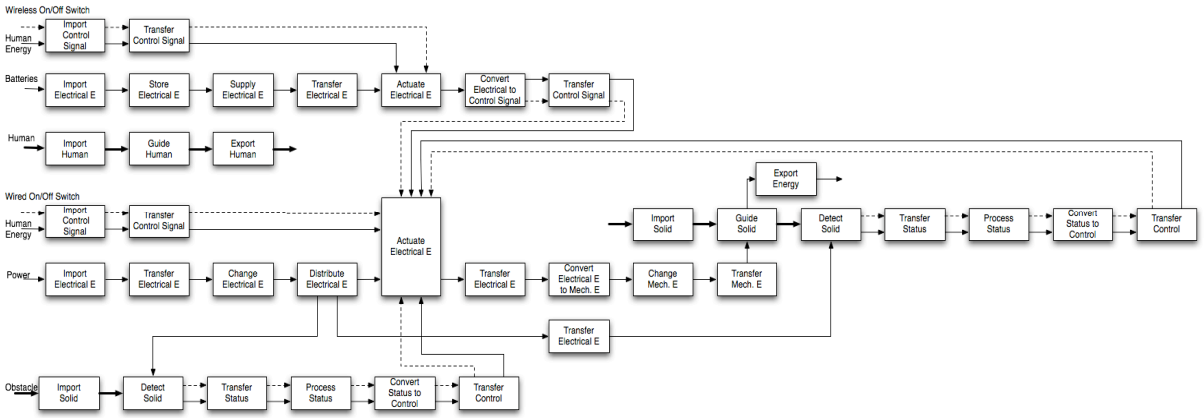

Figure 5. Aggregated functional model of an automatic garage door opener

Each of the signal based function chains identified in the garage door and provided Figures 3 and 4 are built from the templates provided through syntax following the morphology rules. The combined grammar aids in the identification of necessary flows for desired functionalities, which not only aids in the development of independent function-flow chains, but also aids in aggregation of the overall model. Flows fit together better in the final functional model and are more clearly represented with

the inclusion of carrier flow information, which might otherwise be excluded from the functional model.

6 CONCLUSIONS

The Functional Basis Modeling Language is a start to evolve the Functional Basis toward a formal language for functional modeling. Analogies are drawn between FBML and formal languages, and a grammar consisting of syntax and morphology is presented. The signal grammar for modeling signal flows allows for more consistent functional modeling among designers. This uniformity helps to ensure understanding and helps to maintain consistent archival of design information. The signal usage grammar provides a framework for the application of Functional Basis terms, which is demonstrated on an example electromechanical product. A structured modeling language with a clear morphology, syntax, lexicon, graphology, and semantics aids in the automated and manual functional model generation techniques.

Usage grammar addresses the consistency of model structure, and when paired with a consistent taxonomy like the Functional Basis, increases the consistency of functional modeling. Consistency of models improves model-to-model communication among designers and helps to develop the synergy needed to develop an engineering solution for automated design where components must communicate and function across domains.

Future work will focus on the further evolution of the Functional Basis into the Functional Basis Modeling Language and on verification of the validity of the proposed signal grammar. Refinement of the grammar and the development of an analogous syntax and morphology for energy and material flows will be developed. Once grammar consisting of syntax and morphology has been developed for the entire Functional Basis, experiments will be performed with students who are learning and familiar with functional modeling utilizing the Functional Basis to verify the uniformity among models when the refined grammar is applied.

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