

Functional design of mechanical products based on behavior-driven function-environment-structure modeling framework

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Abstract: The relative significance of upstream design activity to downstream design activity is widely recognized, due to its critical role in determining the final product's functionality. Although there are now some general methodologies dealing with functions or reasoning about functions, virtually no commercial CAD system can support functional design. In functional modeling, a design problem is represented in a hierarchy of functions and the behaviors that realize the functions. This paper presents a functional design methodology based on a behavior-driven function-environment-structure (*B-FES*) modeling framework to guide functional design through functional reasoning steps including causal behavioral reasoning (*CBR*) and functional decomposition. The proposed functional design starts from a set of design specifications including functional requirements and design constraints, and results in diverse behavioral schema corresponding to a set of design alternatives. A design example for functional design of a terminal cut-off unit in an automatic assembly system is used to provide a demonstration of the proposed functional design methodology.

I. INTRODUCTION

In the early 1980s, researchers began to realize the impact of design decisions on downstream activities.

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As a result, different methodologies such as design for assembly, design for manufacturing and concurrent engineering, have been proposed. A lot of commercial CAD systems that implement these methodologies have also been developed to provide the industry with advanced geometric modeling and conceptualization techniques owing to its powerful shape manipulation capabilities. The proliferation of commercial CAD systems in the market has provided the extra impetus for the change. However, most of these tools are only applicable in the downstream design activity, which is only half the track of a whole design process of mechanical products. What is more critical is the remaining, upstream design activity, that is, the initial and most abstract stage of the design process, starting with a set of design specifications and resulting in concept variants. This is the area where CAD technology is still not well developed. Conceptual design, being the early stage of design, is characterized by information that is often imprecise, inadequate and unreliable. More importantly, a poorly conceived design concept can never be compensated for by a good detailed design. Essentially this stage is function-laden and function-oriented, because the main design focus at this stage is to find a design solution which is able to achieve the required functions. Functional design (Tor et al., 1998) is a new perspective towards the research of this upstream design activity.

There are now some general methodologies dealing with functions or reasoning about functions (Bracewell & Sharpe, 1996; Umeda et al., 1996; Deng et al., 1999), virtually no commercial CAD system can support functional design. In this paper, we propose a functional design methodology on the basis of our previous work on Behavior-driven Function-Environment-Structure (*B-FES*) modeling framework (Tor, et al., 2001). Functional design is regarded as a constructing process of a consistent and comprehensive *B-FES* functional model of a design by detailing and embodying the design specifications on the *B-FES* functional modeling framework. The methodology can guide functional design through functional reasoning steps including causal behavioral reasoning (*CBR*) and functional decomposition. A design example for functional design of a terminal cut-off unit in an automatic assembly system is used

to provide a demonstration of the proposed functional design methodology, i.e., to demonstrate how a *B-FES* functional model of a product-to-be-designed can be constructed on the corresponding *B-FES* functional modeling framework.

II. FUNCTIONAL DESIGN OF MECHANICAL PRODUCTS

When a designer is assigned a task to design a mechanical product, it is firstly specified by the desired functions of the final design output. Thus the designer's role is to come up with a mechanical product composed of parts such that the assembled product provides the desired functions. Essentially the upstream design activity is function-laden and function-oriented. Functional design (Tor et al., 1998) is a new perspective towards the research of the upstream design activity, and its objective is to provide computer tools to link design functions with the structural (physical) embodiments used to realize the functions. Generally designers agree that function is the most important concept in determining a mechanical product's basic characteristics, because products with problems in their main functions will never sell, no matter how sophisticated their details. By using functional design approach, design efforts can be enabled to be more focused.

The importance of function in design has been well recognized. Chakrabarti and Blessing (1996) pointed out that knowledge of functionality is essential in a wide variety of design-related activities, including generation and modification of designs, comparison, evaluation and selection of designs, and explanation, diagnosis or repair of designs, etc. There are many diverse, even contradictory definitions of function, with different researchers (Bracewell & Sharpe, 1996, Umeda et al., 1996, Deng et al., 1999, and so on) attributing different meaning either to indicate the purpose or the action of a design. But almost all of them indicate that there is a tight coupling between function and behavior. In general, The function of a design refers to what it does, while how it does what it does is its behavior (de Kleer & Brown, 1984).

There are a variety of methodologies for dealing with functions in functional design (Bracewell & Sharpe, 1996; Umeda et al., 1996; Deng et al., 1999). Rather than mapping directly from a desired function to physical structure, functional design is usually treated as a two-step process, first transforming the desired function to a behavioral description and then matching physical structure to this behavior. We believe the explicit use of a behavioral reasoning step provides a good basis to generate design solution, because the behavioral step provides an opportunity to explore a wide variety of solution structures

without prejudice to certain artifacts. Thus we conclude that functional design is not only a design activity but also an effective and efficient methodology to cover the upstream stage of design process. It aims at providing computer tools to link design functions with the behaviors used to fulfill functions, and the structures used to meet the behaviors, and finally achieve the overall design specifications.

III. FUNCTIONAL MODELING IN DESIGN

One of the main difficulties in support functional design is the complexity involved in modeling many facets of a mechanical design product. We refers to this as the modeling problem. Many modeling techniques have been developed and used in science and engineering. Most of them are dedicated to a specific aspect of complex systems by utilizing a structural/behavioral modeling approach. However, these structural/behavioral models are inadequate for functional design that is function-laden and function-oriented. The relatively young functional modeling approach is becoming a promising and leading technique to model a design and requirements from its functional aspects so as to allow reasoning about its function for various activities.

Umeda et al. (1996) developed a Function-Behavior-State (*FBS*) modeler to support functional design. The *FBS* modeler regards functional decomposition as of two types: causal decomposition and task decomposition. Deng et al. (1999) devised a dual-step Function-Environment-Behavior-Structure (*FEBS*) modeling framework, in which the causal decomposition of function (Umeda et al., 1996) has been extended by incorporating the working environment of the system-being-designed so that the modeling hierarchy is more comprehensive. Deng et al. also suggest a dual-step modeling procedure – initial functional decomposition and causal behavioral process generation. However, Deng et al.'s dual-step *FEBS* modeling framework is inflexible and computation-expensive due to its fixed up-down modeling strategy (from initial functional decomposition to causal behavioral process generation). The design problem may be decomposed “too fine”, which may cause combinatorial explosion. Furthermore, any problem encountered in the second step has to be solved at that level and can not be passed back to the previous level for further functional decomposition. These problems have been solved in our recent work on *B-FES* functional modeling framework (Tor et al., 2001), which will be briefly described in the following subsection.

It should be noted that there are other functional models that could be used to support functional

design, for example, Qian & Gero's [16] *FBS* Path, Goel's [17] *SBF* model and Prabhakar & Goel's [18] *ESBF* model. However, a discussion of these approaches is beyond the scope of this paper.

3.1. Brief description on *B-FES* functional modeling framework

Figure 1 shows the features of the *B-FES* functional modeling framework (Tor et al., 2001) that consists of three layers, namely function layer, behavior layer and environment layer. It is the extension and refinement of the initial dual-step

necessary to achieve the main functions. The behavior layer describes the underlying principles of the main functions and sub-functions. For ease of implementation, a structure is implicitly involved in a behavior in the behavior layer, because the structural configuration is determined once the behavioral schema is fixed. The environment layer describes the working environment supporting the design object.

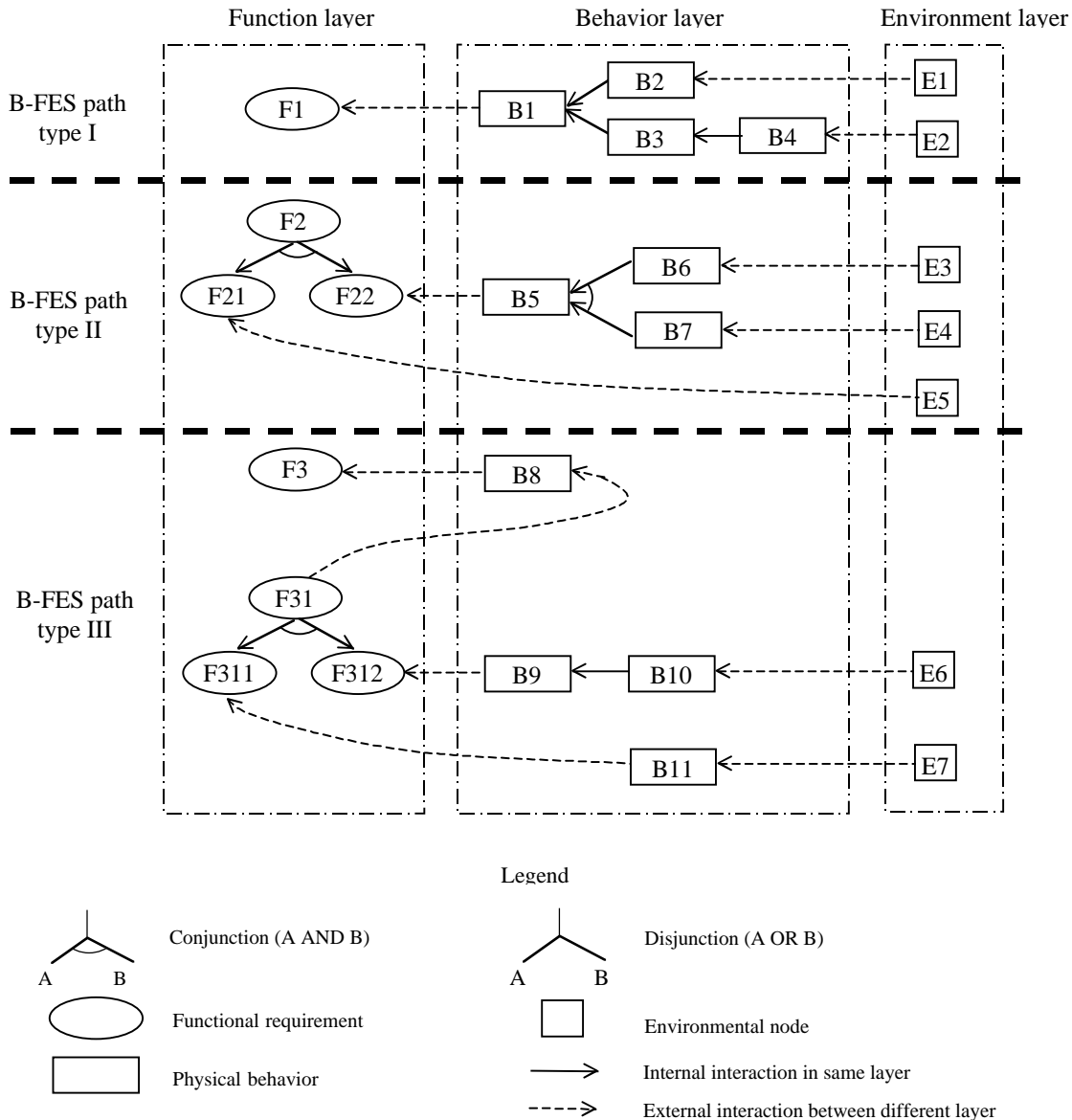


Figure 1 The features of the *B-FES* functional modeling framework

(Tor et al., 2001).

FESB modeling framework. The function layer defines the main functions and the sub-functions

In this *B-FES* functional modeling framework, we have devised a behavior-driven modeling strategy.

Behavior is represented as input-output action in terms of driving input (a kind of functional requirement), behavior actor (structure) and functional output (intended output action). The starting point of the proposed strategy is to search for the matching behavior whose functional output can achieve the desired function (i.e., a kind of functional requirement). The desired function will only be decomposed into simple sub-functions for further causal behavioral searching process when no direct matching behavior exists. The proposed approach can prevent the domain problem being decomposed “too fine”, causing combinatorial explosion. In the behavior layer, behaviors are interconnected with each other, with one’s functional output matching the other’s driving input so as to achieve an external function specified in the function layer. All the interconnected behaviors must satisfy the imposed design constraints. The behavioral searching process through causal reasoning is defined as the Causal Behavioral Reasoning (*CBR*) process. In the environment layer, environmental nodes provide the functional outputs to achieve the driving inputs of behaviors in the behavior layer, or the sub-functions in the function layer. When all the newly generated functional requirements during *CBR* process are available in the environment, the *CBR* process can be terminated and result in a behavioral schema, which should be evaluated to make a best selection.

In order to establish a consistent *B-FES* functional model of a design system, usually various *B-FES* path types in *B-FES* functional modeling framework can be used by either matching a desired function with a behavior or decomposing it into sub-functions.

Though various design characteristics related to functional design, are considered to construct a consistent and comprehensive functional model, the *B-FES* functional modeling framework is still very flexible, and quite different from initial dual-step *FEBS* modeling framework (Deng et al., 1999). The latter is inflexible and computation-expensive due to its one-way and up-down modeling strategy. In contrast, the modeling strategy in *B-FES* functional modeling framework is in a flexible two-way mode. For example, a function in the function layer can be achieved by a behavior in the behavior layer, as is the transformation from the function layer to the behavior layer; on the other hand, a complicated driving input of a behavior in the behavior layer can be projected into the function layer to be broken down into sub-functions, as is the transformation from the behavior layer to the function layer.

Functional design process on the *B-FES* functional modeling framework

In this paper we consider that functional design is to

construct a consistent and feasible *B-FES* functional model of a design by detailing and embodying the design specifications including overall functional requirements and design constraints on the *B-FES* functional modeling framework.

Our proposed functional design (Figure 2) starts from a set of design specifications and results in diverse behavioral schema corresponding to a set of design alternatives via a *CBR* process. These design alternatives are then evaluated to take a best selection. During the *CBR* process, if a desired function (overall functional requirement, or driving input of a retrieved behavior) is too complex to be achieved by any available behavior directly, the desired function should be broken down into simple sub-functions, i.e., through functional decomposition process, to facilitate further *CBR* process. Unless a selected best design alternative is already a complete design solution which meets the whole design specifications, the above *CBR* process and functional decomposition will be repeated to refine the functional hierarchy and behavioral schema.

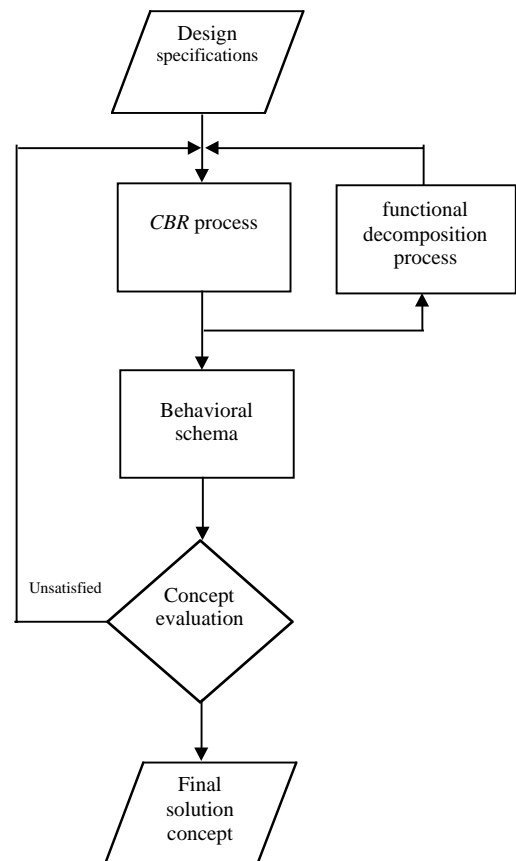


Figure 2 Basic flow of functional design process

IV. CONSTRUCTING A *B-FES* FUNCTIONAL MODEL: A FUNCTIONAL DESIGN EXAMPLE

This section discusses how a *B-FES* functional model can be constructed through the proposed *B-FES* functional modeling framework, so as to perform functional design of a mechanical product.

To facilitate the illustration, a design example for functional design of an automatic assembly system for manufacturing electronic connectors (From Web Page <http://www.molex.com/training/bce/index.html>) will be studied. The said automatic assembly system comprises of a vibrator bowl feeding unit, a housing singulator, a walking beam unit, a terminal feeding unit, a terminal cut-off unit, a terminal insertion unit and a terminal bending unit. This design example will focus on the functional design for a terminal cut-off unit, through the proposed *B-FES* functional modeling framework. To facilitate reading, the schematic geometric structures of some device behaviors are shown in figure 3. The authors believe that the approach can be extended to other mechanical systems.

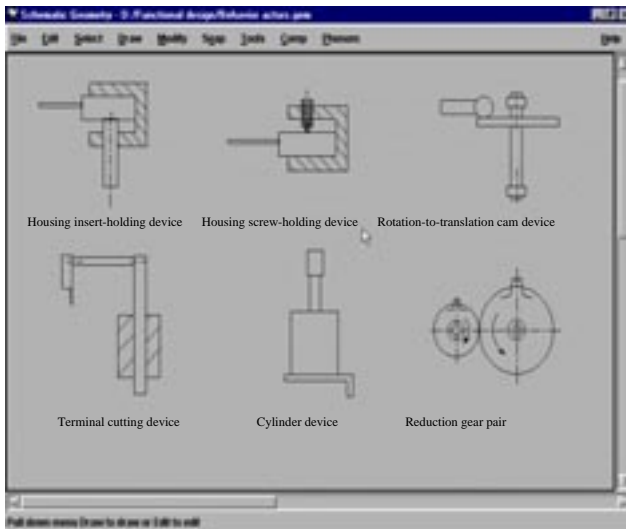


Figure 3 Schematic geometric structures of some device behaviors.

4.1. Problem description

Assume the following functional design specifications and environment specifications are given:

Design task is to design a terminal cut-off unit with an overall functional requirement:

Cut terminal after holding housing.

(2) The following design constraint applies:

High precision.

The environment can provide the following environmental outputs:

a. *Provide pneumatic air;*

b. *Provide electric power;*

c. *Fix device.*

Besides the above design specifications and environment specifications, some design criteria are also necessary, but have been omitted here so as to focus on the functional aspects of *B-FES* functional model.

4.2. Construction of a *B-FES* functional model for functional design

With the construction of a *B-FES* functional model (Figure 4) through the proposed *B-FES* functional modeling framework, functional design process proceeds in the following logical steps: (The legend used in figure 1 is still applied in figure 4)

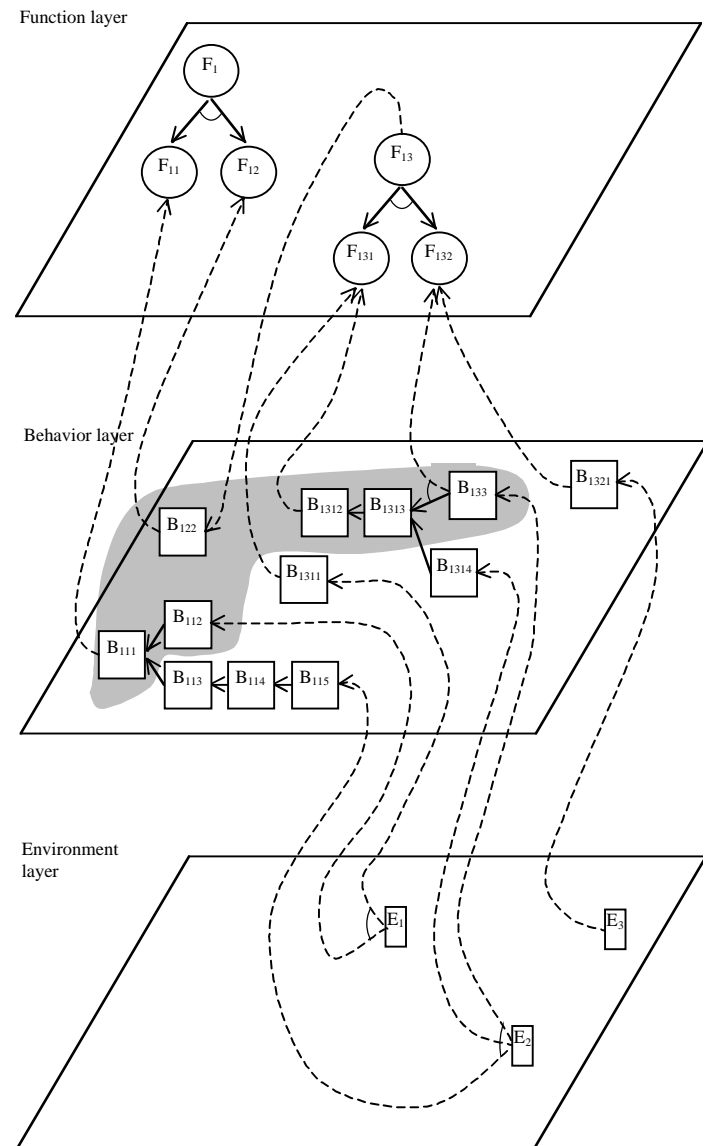


Figure 4 *B-FES* functional model in the functional design example

(1) Firstly put the overall functional requirement F_1 in the function layer, and a set of environmental nodes including E_1 , E_2 and E_3 in the environment layer, and try to develop the behavioral schema in the behavior layer through causal behavioral reasoning (CBR) or functional decomposition.

Where:

F_1 : Cut terminal after holding housing;

E_1 's environmental output: Provide pneumatic air;

E_2 's environmental output: Provide electric power;

E_3 's environmental output: Fix device.

(2) The starting point of the modeling strategy is to search for the matching device behavior whose functional output can achieve the desired function F_1 in the function layer. All retrieved device behaviors must satisfy the imposed design constraint: *High precision*, and this point will not be repeated in the following discussion. Assuming no matching device behavior is found, the desired function F_1 should be decomposed into simple sub-functions F_{11} and F_{12} for further CBR.

Where:

F_{11} : Hold housing.

F_{12} : Cut terminal.

(3) For the desired function F_{11} , the starting point of the modeling strategy is to search for the matching behavior whose functional output can achieve the desired function F_{11} in the function layer. It is found either behaviors B_{111} or B_{116} can achieve F_{11} . But B_{116} is discarded because it doesn't satisfy the constraint requirement: *High precision*. Then only the behavior B_{111} which satisfies the design constraint is developed in the behavior layer, and its driving input *Provide translational motion* is taken to be the new functional requirement. Similarly, in the behavior layer, the behavior B_{112} is developed with its functional output *Provide translational motion* matching the behavior B_{111} 's driving input. Now B_{112} 's driving input *Provide pneumatic air* becomes the new functional requirement. Because the environment E_1 in the environment layer can satisfy *Provide pneumatic air*, this search branch is terminated.

Where:

B_{111} : Housing insert-holding device;

B_{112} : Cylinder device;

B_{116} : Housing screw-holding device.

(4) Similarly, in the behavior layer, B_{111} 's driving input *Provide translational motion* can also be matched by B_{113} 's functional output *Provide translational motion*; B_{113} 's driving input *Provide low speed rotary motion* can be satisfied by B_{114} 's functional output *Provide low speed rotary motion*; B_{114} 's driving input *Provide high speed rotary motion* can be satisfied by B_{115} 's functional output *Provide*

high speed rotary motion; and B_{115} 's driving input *Provide electric power* can be satisfied by environment E_2 in the environment layer. This search branch is also terminated.

Where:

B_{113} : Rotation-to-translation cam device;

B_{114} : Reduction gear pair;

B_{115} : Motor device.

Now the CBR process for realizing function F_{11} : *Hold housing* has been finished with two feasible branches being developed. Figure 5 shows a partial detailed representation of CBR process.

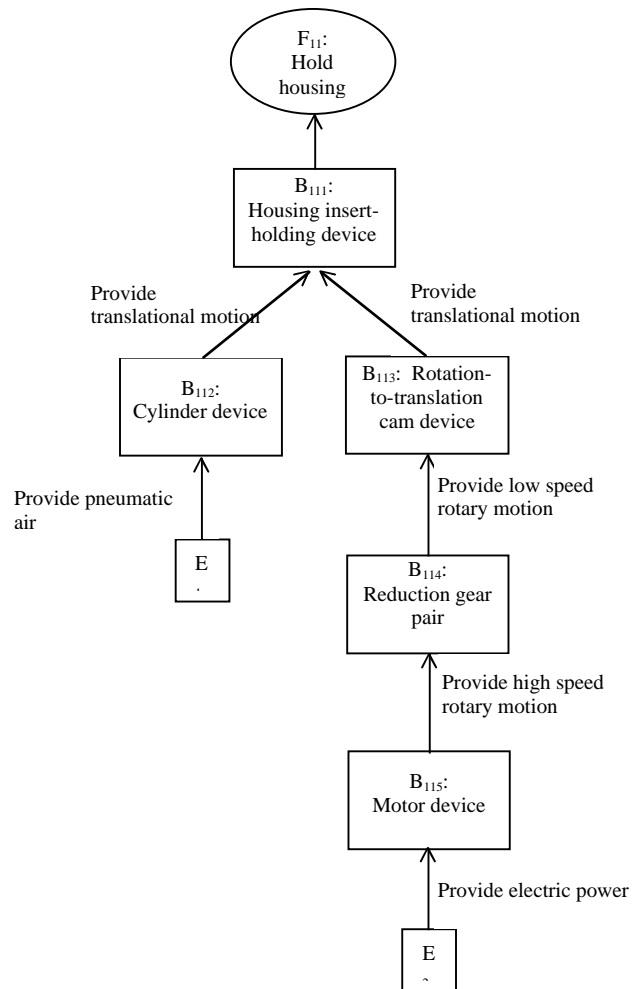


Figure 5 Partial detailed CBR process

(5) To achieve the desired function F_{12} in the function layer, a behavior B_{122} is developed in the behavior layer with its driving input *Provide translational motion within a certain range* becoming the new functional requirement.

Where:

B_{122} : Terminal cutting device.

(6) Because the driving input of the behavior B_{122} is too complicated to be achieved by any available behavior directly, it is projected back to the function layer as F_{13} , and broken further down into less complex sub-functions F_{131} and F_{132} .

Where:

F_{13} : Provide translational motion within a certain range;

F_{131} : Provide translational motion;

F_{132} : Control moving range.

(7) Then, in the behavior layer, the behavior B_{1311} is developed with its functional output *Provide translational motion* matching the desired function F_{131} , and its driving input *Provide pneumatic air* is satisfied by the environment E_1 in the environment layer. Similarly, an alternative CBR branch to achieve the desired function F_{131} can be developed.

Where:

B_{1311} : Cylinder device;

B_{1312} : Rotation-to-translation cam device;

B_{1313} : Reduction gear pair;

B_{1314} : Motor device.

(8) With the behavior B_{1321} developed in the behavior layer to achieve the desired function F_{132} , the CBR branch for F_{132} can also be developed. In addition, the behavior B_{133} can be retrieved with its functional outputs achieving both F_{132} : *Control moving range* and B_{1313} 's driving input *Provide high-speed rotary motion*.

Where:

B_{1321} : Limit control switch;

B_{133} : Step motor device.

(9) Check if there are any unexplored searching branches. If there are none, terminate the modeling process. A list of 6 theoretically feasible concept variants produced through construction of B-FES functional model are shown below.

..... CONCEPT VARIANTS ARE.....

Variant #1 → Housing insert-holding device + Cylinder device + Terminal cutting device + Cylinder device + Limit control switch

Variant #2 → Housing insert-holding device + Cylinder device + Terminal cutting device + Rotation-to-translation cam device + Reduction gear pair + Motor device + Limit control switch

Variant #3 → Housing insert-holding device + Cylinder device + Terminal cutting device + Rotation-to-translation cam device + Reduction gear pair + Step motor device

Variant #4 → Housing insert-holding device + Rotation-to-translation cam device + Reduction gear pair + Motor device + Terminal cutting device + Cylinder device + Limit control switch

Variant #5 → Housing insert-holding device + Rotation-to-translation cam device + Reduction gear pair + Motor device + Terminal cutting device +

Rotation-to-translation cam device + Reduction gear pair + Motor device + Limit control switch

Variant #6 → Housing insert-holding device + Rotation-to-translation cam device + Reduction gear pair + Motor device + Terminal cutting device + Rotation-to-translation cam device + Reduction gear pair + Step motor device

-----Total of 6 variants generated-----

(10) According to Pahl & Beitz (1996), we evaluate all the resulted concept variants to narrow the choice. This final decision-making phase is the phase of concept evaluation and selection where all the concept variants generated are evaluated with respect to each other and the highest scoring variants are selected in order of value. The values by which the concept variants are evaluated and decided upon are generated here by conducting a concept evaluation based on technical and economic criteria which are selected based on the requirements of the automatic assembly system. In this example, Concept variant #3 is eventually chosen as the best solution concept (marked with hatching in Figure 4). Figure 6 shows the graphical representation of Variants #3.

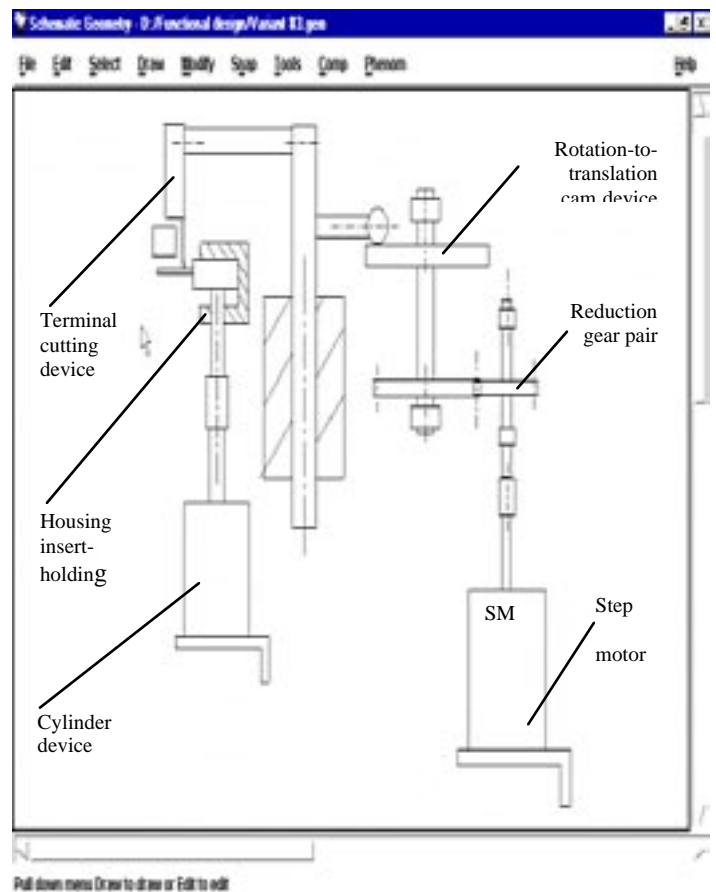


Figure 6 Graphical representation of concept variant #3 for terminal cut-off unit

V. CONCLUSION

In this paper, a functional design methodology was proposed on the basis of our previous work on *B-FES* functional modeling framework (Tor, et al., 2001). Functional design is regarded as a constructing process of a consistent and comprehensive *B-FES* functional model of a design by detailing and embodying the design specifications on the *B-FES* functional modeling framework.

During functional design, the starting point of the modeling strategy is to search for the matching behavior whose functional output can achieve the desired function (i.e., a kind of functional requirement). A desired function is not decomposed unless a behavior cannot be found that meets the desired function. The adopted behavior-driven modeling strategy can reduce the possibility of combinatorial explosion that can occur during functional decomposition.

The proposed approach is limited to creating new configurations (combinations) from a library of standard physical behaviors. It will not generate innovative designs that require the use or invention of new physical behaviors. However, the methodology can generate specifications for new physical behaviors and thus guide a designer in the search for new innovative designs.

A design example for functional design of a terminal cut-off unit in an automatic assembly system has been used to provide a demonstration of the proposed functional design methodology.

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