Solid Freeform Fabrication 2016: Proceedings of the 27th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Conceptual design for assembly in the context of additive manufacturing

S. Yang* and Y. F. Zhao*

*Department of Mechanical Engineering, McGill University
Montreal, Quebec, Canada H3A 0C3

Abstract

As additive manufacturing (AM) emerges as an end-of-use product manufacturing process, design for additive manufacturing (DFAM) as a new design philosophy receives more and more attention. However, current DFAM research focuses on downstream and part-level design activities such as structural optimization and design rules. Design freedom enabled by AM such as, part consolidation and function integration has not been fully investigated. These design freedom forces designers to rethink about assembly-level design so as to embrace integrated functionality. To understand how to integrate AM characteristics into design process, three questions are investigated: 1) why does conceptual design need to be redone for assembly? 2) what has changed by AM in design concept generation? 3) how to do conceptual design in AM context? Afterwards, a conceptual design framework is proposed to aid design flow management. In the end, a throttle pedal redesign case is demonstrated as verification of the proposed design framework.

Keywords: assembly-level DFAM, conceptual design, additive manufacturing, functional design, FBS modeling

1. Introduction

Additive manufacturing (AM) is defined as "a process of joining materials to make object from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [1]. This layer-wise manufacturing process makes it possible to manipulate material distribution and composition without any other tools. The design freedom enabled by such a technique includes shape complexity, hierarchical complexity, material complexity, and function complexity [2, 3]. All these new features of AM force designers to incorporate AM-enabled design freedom into the design stage and rethink about how to make a better engineering design. However, as Yang et al. [3] and Laverne et al. [4] pointed out, current Design for Additive Manufacturing (DFAM) research focuses on part-level and downstream design activities such as structural optimization and design rules without the possibility to be extended for assembly-level applications. These applications mainly refer to part consolidation and function integration, which helps to reduce part count and product weight and size, to eliminate assembly difficulty, and to improve design robustness. All these benefits make assembly-level DFAM receive more and more attention.

In comparison with part-level DFAM, assembly-level applications have to deal with relations between components in order to decide if two components can be consolidated or not. Moreover, part consolidation will lead to function integration and even a coupled design which is not favoured by Axiomatic Design [5]. How to make the trade-off in design complexity is unclear. Furthermore, assembly-level applications require more complete information than the part-level counterpart. For example, the boundary of the system of interest should include necessary void information within the convex hull of the chosen components. Apparently, all these three aspects are intensively related to the conceptual design stage of the system of interest. To upgrade DFAM philosophy into the assembly-level design to embrace the advance in function integration and part consolidation, a comprehensive understanding of how a product is developed is necessary, especially the conceptual design stage. Besides, conceptual design has its practical value because the initial stage of design accounts for 80%-90% of the product success [6]. Unfortunately, existing Design Theory and Methodology (DTM) cannot support the need of taking advantages of AM-enabled design freedoms [3, 7]. From conventional design philosophy point of view, it is advocated to design simply and dissect products to ease assembly operation and reduce manufacturing difficulties. Therefore, the problem of conceptual design for assembly in the context of AM cannot be solved by conventional DTM.

In order to shed light into conceptual design and provide a methodological way to apply AM-enabled design freedom, three questions are to be investigated in this paper.

- Question 1: how does existing conceptual design philosophy work?
- Question 2: what are the challenges in the context of AM?
- Question 3: how to do conceptual design with appropriate AM knowledge input?

These questions are discussed in Section 2, 3, and 4 respectively. A function-behavior-functional entity-functional feature (FBFF) design synthesis method is proposed to answer Question 3. Afterwards, an example of a throttle pedal is investigated in terms of conceptual redesign. Finally, the paper is wrapped up with conclusions and further research.

2. Existing conceptual design philosophy

Ideally, product design process needs to understand the nature of decision making and the constraints in different design phrases. In this section, several design methodologies involving the concept of conceptual design are discussed. These methods include General Design Theory (GDT) [8], Systematic Design approach [9], VDI 2221 [10], and Axiomatic Design [5]. In this paper, function is defined as a description of behavior abstracted by human through recognition of the behavior in order to utilize the behavior [11].

2.1 General Design Theory

GDT deals with concepts that only exist in our recognition and it uses set theory to explain knowledge manipulation in the design process. It has a basic manifesto that knowledge can be mathematically formalized and operated. Therefore, design process is a mapping from function space to attribute space. As shown in Figure 1, function space is a complete set of function entities. Therefore, design solutions can be regarded as the results of logical operations of entities concepts. Afterwards, an entity that can fulfill these design requirements are enriched with abstract concepts. If there is no design solutions found, then knowledge in the first step is incomplete and it becomes the core step of design synthesis. Otherwise, if such an entity concept as the design solution is found, the solution is mapped from function space to attribute space. Then, the neighborhood of the entity in the attribute space is analyzed to obtain attributive information for production. These attributive information includes shape, geometry, material, etc. GDT helps to understand the design process from an entity point of view. Given ideal knowledge, design will be the results of logical operation of function entities and attribute entities.

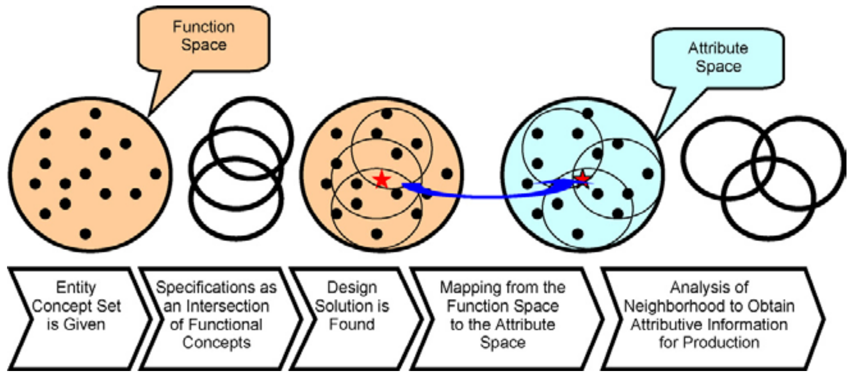


Figure 1 Design process in ideal knowledge [12]

2.2 VDI 2221 and Systematic design approach

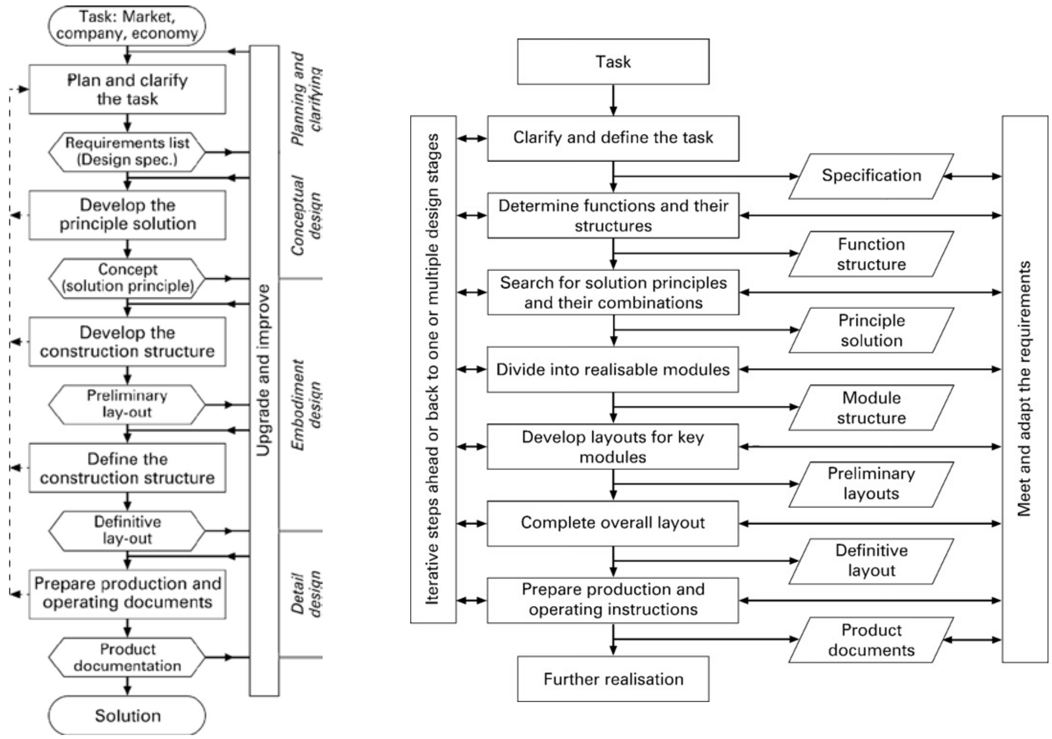
The most well-known design method in practice is the Systematic Design approach by Pahl and Beitz [9]. In this design method, design process is comprised of four phrases: planning and clarifying, conceptual design, embodiment design, and detail design. In the conceptual design phrase, design requirements are interpreted into the principle solution and then, the principle solution is developed into a design concept (Figure 2 a). Similarly, VDI 2221 [10] shares the same procedure but it makes the transition from design requirements to layouts more explicit as shown in Figure 2 b. In VDI 2221, the counterpart of conceptual design covers steps of "determine functions and their structures", "search for solution principles and their combinations", and "divide into realizable modules". Besides, Systematic Design approach models function as input-output flow of energy, material, and signal. This function model helps to do functional decomposition based on the causal relation between functions.

2.3 Axiomatic design

In Axiomatic design, the best design solution is supposed to satisfy two axioms [5]: maximum independence of functional elements and minimum information content. The design process (Shown in Figure 3) is divided into four domains: customer domain, functional domain, physical domain, and process domain. The counterpart of conceptual design in Axiomatic Design is the mapping from the functional domain to the physical domain, which also involves a vertical functional decomposition process within the functional domain. The main contribution of Axiomatic Design is providing a perceptual way to understand a general design process and a mathematic way to evaluate design according to the design matrix and the information axiom.

2.4 Discussion

As shown on the above, although GDT, VDI 2221, Systematic Design approach, and Axiomatic Design vary in the form of representation, they all cover two design activities in the concept developing stage: functional decomposition and design synthesis. Functional decomposition refers to process of decomposing high-level functions to lower ones until specific design solutions are available. Design synthesis means the process of mapping functions (or functional requirements) to concrete physical forms. In practice, these two design activities are not sequential but iterative because of the imperfection of knowledge (of designers). In this sense, conceptual design can be abstracted as the enrichment of functions and the realization of functions.



(a) Systematic Design approach (b) Recommended design process (VDI 2221)

Figure 2 Systematic design approach [9] and VDI 2221 [10]

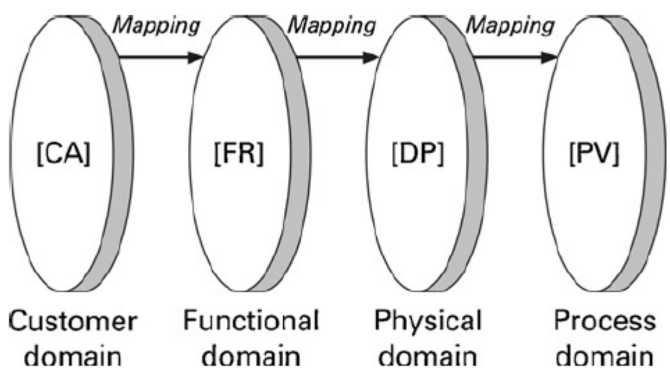


Figure 3 Axiomatic design process [5]

The relation between functional decomposition (or functional analysis [13]) and design synthesis is shown in Figure 4. The initial input of conceptual design is functional requirements and the ultimate output is design concepts. Between functional analysis and design synthesis, there may be an iterative process because functional analysis process may be aided by the hierarchy of physical product.

Abstracting the conceptual design process into functional analysis and design synthesis helps to characterize the impact of AM on conceptual design. All the studied design methodologies can support developing design concepts; however, they are so general and abstract that they are insufficient to lead designers in terms of how to develop a new design concept. When it comes to AM context, the problems will be how functional analysis and design synthesis are affected by

AM-enabled design freedom and how to do functional analysis and design synthesis to find AM-enabled design concepts.

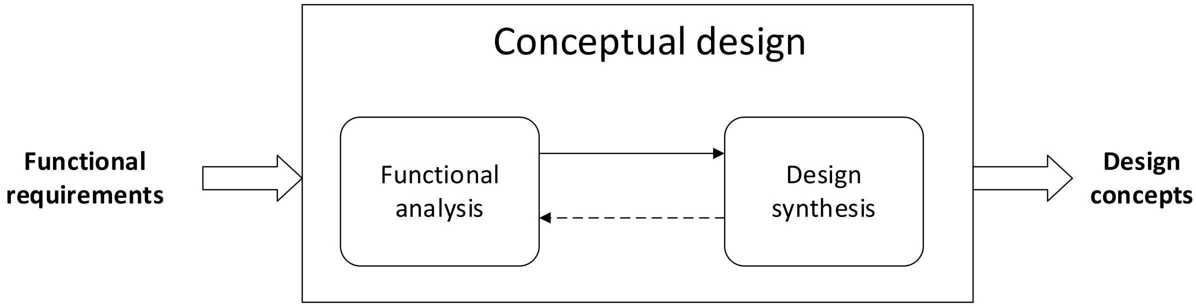


Figure 4 Main design activities in the conceptual design stage

3 Challenges in the AM context

The investigation of the impact of AM on conceptual design can be simplified as that of the influence on functional analysis and design synthesis. According to the definition of functional analysis, the main tasks will be to decompose the overall function to sub-functions until sub-functions can be realized by available physical forms. Based on the classification of product innovation levels [14], most of redesign is to achieve incremental innovation rather than radical innovation because the working principles behind the new design concept is the same as the old one. Taking the design scenario of a new power system for a new car model, a design concept of solar system and a design concept of a petrol-driven system are quite different in terms of working principles; therefore, this design scenario can be regarded as radical innovation. In contrast, only changing the physical form without altering the working principles does not change the function structure.

AM is more suitable to stimulate incremental innovation rather than radical innovation. Firstly, it is difficult and unreasonable to expect companies to invest significantly to come up with a totally new design concept especially with high complexity, for example, civil aircrafts. Secondly, to pursue incremental innovation makes it easier for designers to repeat their old ways of functional design, which accelerates the product development cycle. In contrast, radical innovation is realized by a thorough change in the design concept, but AM cannot make it that far yet in most cases. For example, consolidation of horizontal stabilizer and vertical stabilizer is possible depending on the improvement in the control system instead of manufacturing techniques. Since the whole working principles are not altered, functional analysis process still follows the process of top-down decomposition and the resultant function structure will be the same as the old one. In conclusion, AM has minor effect on functional analysis process.

In design synthesis stage, the main tasks are to map low-level functions to concrete physical forms. Design synthesis is one of the most heated research topics in the design community. Design synthesis in some literatures are called functional design, functional modeling[15] or functional reasoning[16]. Since this paper emphasizes on the impact on design synthesis, it does not matter which functional modeling method is taken. Function-behavior-state (FBS) functional modeling method [16] regards function, behavior, and state as independent entities in the design process. Behavior is an aggregate of a set of states with respect to external stimuli on the basis of its structure and physiochemical properties. State typically refers to the multiple state of physical structure. FBS functional modeling scheme has high expressive power over the mapping from design intent (function) to physical structure. As shown in Figure 5, a given Function A is mapped to a desired Behavior B according to human recognition abstraction. Then, Behavior B is realized by the transition of State C to D via physical structure. Thus, the mapping from a function to its corresponding physical form is accomplished. For example, given a function “generate light”, the desired behavior is “light on via electricity”, then the state will be “switch’s state is changed from off to on”. Revisiting the characteristics of AM, we know that AM is able to manipulate material composition and distribution. It means that AM is able to change morphology, topology, and material properties. In conventional design philosophy, design is limited by designers’ knowledge of existing shapes, materials, and manufacturing processes. Therefore, the resultant change by AM will be the physical phenomena, that is, the mapping between behaviors to physical structures. For example, to realize the function “grab things”, the behavior will be “supporting force is larger than gravity”, then the AM-enabled feature will be “a curved surface with textures”.

In conclusion, AM-enabled design freedom only enriches the mapping relations between the desired behavior and the corresponding physical structures. The processes before this mapping including functional analysis and the recognition of desired behavior are not changed by AM.

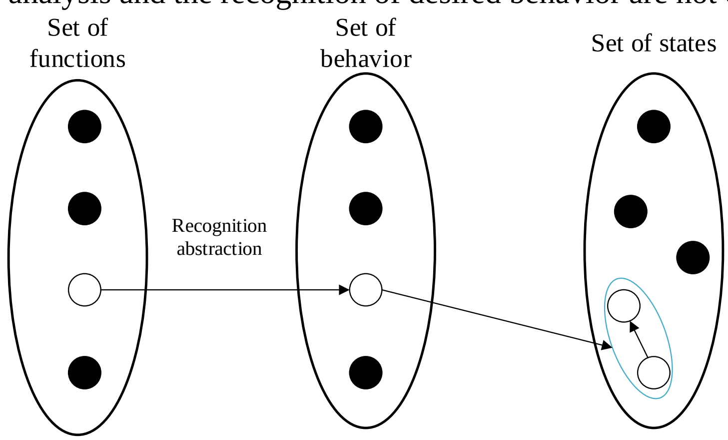


Figure 5 FBS modeling scheme

4 Proposed design synthesis strategy

Although it becomes clear that AM only imposes influence on the mapping from behavior to the physical form, how to stimulate designers’ creativity to come up with novel designs is still challenging. Traditionally, FBS design synthesis is realized by functional components or standard device. For example, to realize a function “store water”, corresponding physical structure will be “a container”. After that, the cross-section shape and material is chosen from the limited regular shapes and materials respectively. Constrained by available manufacturing processes and cost, design parameters are much less. In contrast, if manufacturing consideration is neglected, a container with various cross-section shapes are possible and it may be coated with heat insulation materials by AM. Here comes the question of how to stimulate designers who are novice in AM to think in an “AM way”.

Following the similar concept of function-behavior-state design synthesis strategy, a function-behavior-functional entity-functional feature (FBFF) design strategy is proposed in this paper. Functional entity is defined as the abstraction of physical object to achieve the desired behavior. Functional feature is the concrete form of functional entity. Revisiting the case of the function "store water", we can conclude that the desired behavior is "hold water from leaking". The successive functional entity is "a semi-closed space" and the functional feature could be any surfaces satisfying volumetric requirements. The mapping relations and knowledge input is shown in Figure 6. The mapping between function and behavior remains the same. Changes start at the mapping from behavior to functional entity with AM knowledge 1 (AMK1) as additional inputs to enrich options in the set of functional entity. AMK1 mainly refers to exceptional material properties enabled by AM, such as new materials and functional graded materials. The second change is the mapping from functional entity to functional feature with AM knowledge 2 (AMK2) as additional inputs to enrich functional feature alternatives. Physical phenomena refer to natural physiochemical laws such as Newton's law and Bernoulli Equations. AMK2 mainly implies the innovative geometric, topology, and materials realized by AM. In this sense, functional features can be form features and material features. For either a form feature or a material feature, it is modeled as a set of geometric, material distribution (topology), and material function. If the material is homogeneously distributed, the material function is a constant. If the material is function graded material (FGM), the material function could be represented by a voxel model [17] or an implicit model. It should be noted that the synthesis of functional features depends on other requirements as well if degrees of satisfaction of function [18] is considered. Compared with conventional design philosophy, as long as AMK1 and AMK2 are appropriately extracted, encoded, and delivered to designers at right sequence, FBFF design synthesis strategy can facilitate more design solutions to be found as shown in Figure 6 (the blue oval).

A typical example of applications of the FBFF design synthesis approach is the morphing wing design. Traditional wings are designed as a compromise in geometry which allows the aircraft to fly at a range of flight conditions, but the flight performance at each condition is sub-optimal [19]. As one of the solutions, it requires the airfoil to change shape in different flight conditions. Assume that the desired behavior is "change skin profile with respect to speed", then enabling AMK1 is "a micro-structure has multiple states". The synthesized functional feature will be a surface with material which is sensitive to pressure and has multiple stable states. Due to the complicated internal structure, this synthesis design solution is promisingly realizable by AM.

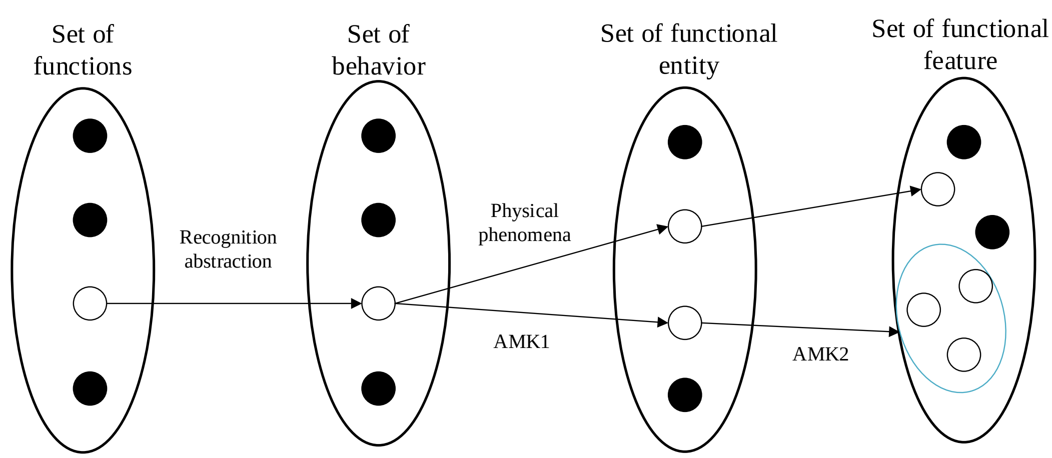


Figure 6 Function-behavior-functional entity-functional feature design synthesis strategy

5 Integrated FBFF in a redesign context

In a redesign process, there are normally limited inputs such as a CAD model and possible design requirements. Systematic quality management principles require complete tracking of product information from details back to design rationale and customer needs [20] and a mere geometric model is insufficient for recording such information. In this paper, the given CAD model serves as the starting point to understand working principles of the old design. The method can be taken is functional analysis, through which implicit functional information can be made explicit.

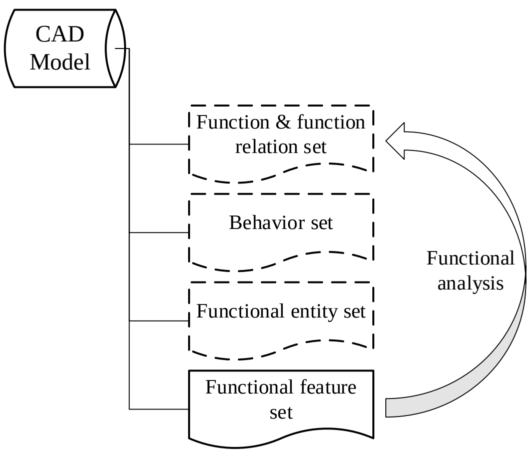


Figure 7 Implicit information of a CAD model

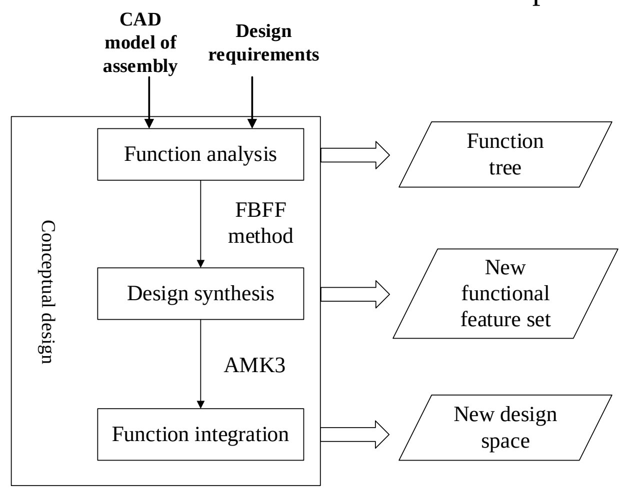


Figure 8 Redesign flow

As shown in Figure 7, FBFF-based functional information model should contain ontologies such as function & function relation, behavior, functional entity, and functional feature. Among these ontologies, only functional features are explicit in the CAD model. Once functional information becomes clear, FBFF method is applied to synthesize new functional features and these new functional features can be investigated if they can be consolidated into one design space. The criteria are AM knowledge 3 (AMK3). AMK3 should deal with four aspects of AM characteristics: part consolidation, embedded components, articulated kinematics, and general AM constraints (e.g. volume and tolerance). If selected functional features are suitable to be consolidated, then function integration process is implemented to generate a new design space as the new preliminary layout. Functional analysis, design synthesis, and function integration forms the conceptual design phase as shown in Figure 8.

6 Case study

To demonstrate how the proposed FBFF design synthesis approach works in the conceptual redesign of an assembly, a throttle pedal is exemplified with appropriate complexity. As shown in Figure 9, the throttle pedal is comprised of 12 components without washers and fasteners. When a force is applied on the pedal, the lever transfers torque to the D-shape pin and the potential meter convert the angular motion to digital signal to control speed. To restrict the range of rotation, a rotation limit is needed. The maximum applied force is 250 lbs.

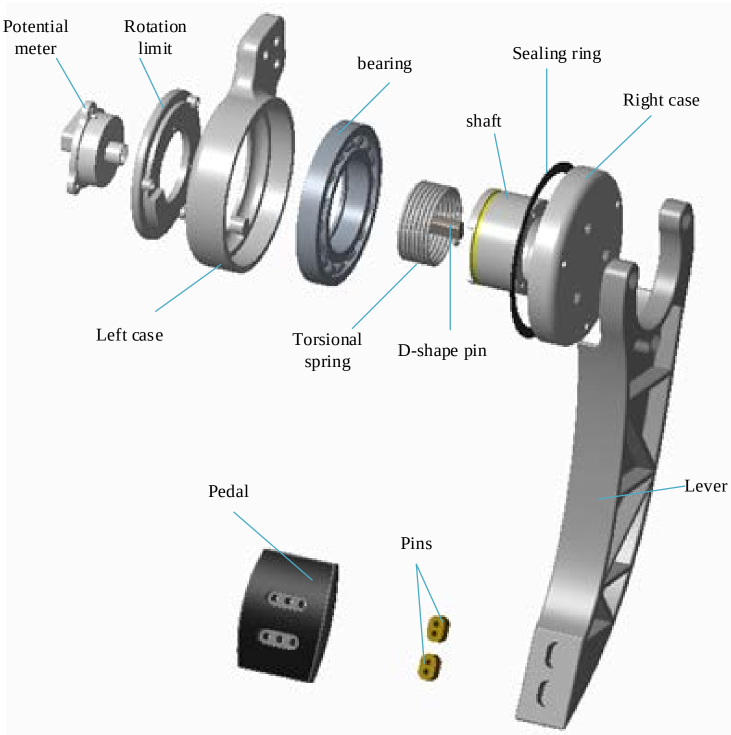


Figure 9 exploded view of a throttle pedal

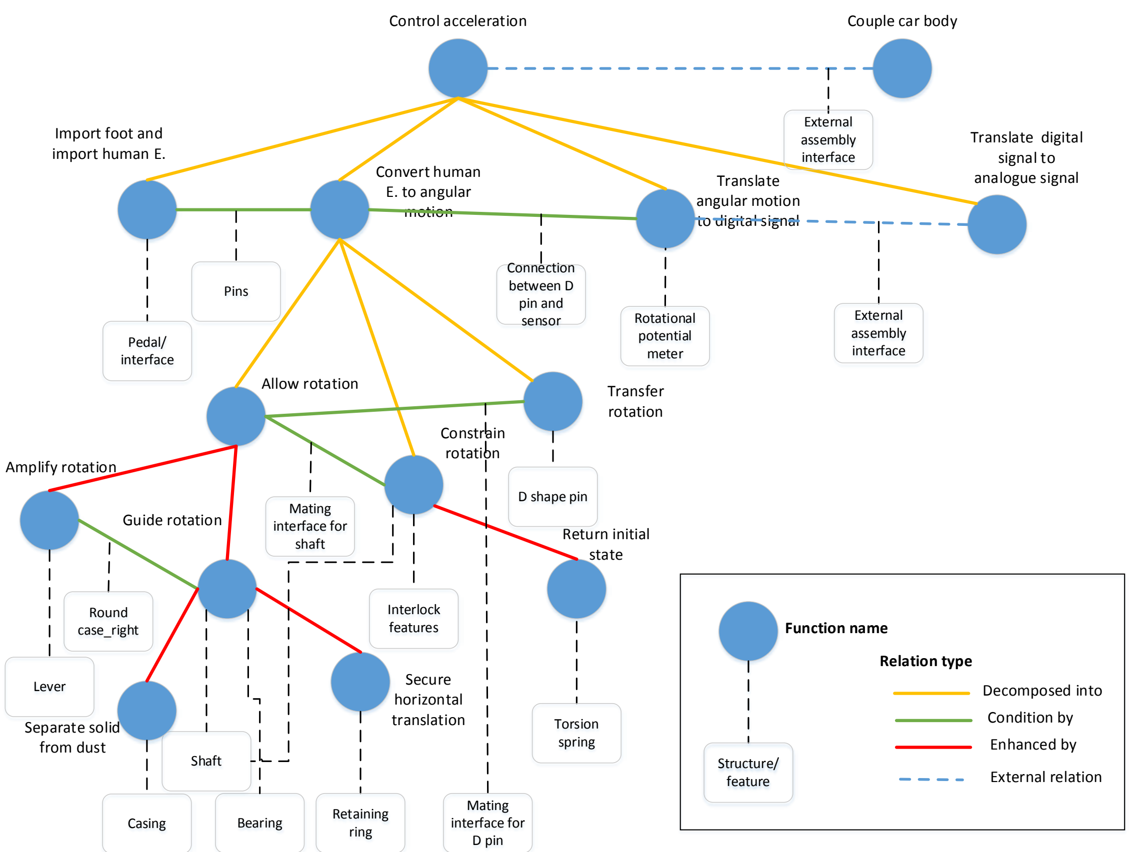


Figure 10 function tree of the throttle pedal

Functional analysis

According to designers' knowledge of function-component mappings, functions of each component can be deduced. It should be noted that a concept of function relation is introduced to characterize relation between functions instead of physical relations. Function relations include decomposed-into, conditioned-by, enhanced-by, and external relations. Decomposed-into relation highlights function hierarchy while conditioned-by relation characterizes causal relations between functions. Enhanced-by relation signifies function redundancy. Because the system of interest is a part of a product, the system boundary is confined by external relations. As shown in Figure 10, functions and function relations construct the function tree. In some cases, some functions have already been integrated into one component.

Design synthesis

Based on the results of functional analysis, functional features should be identified and FBFF design synthesis should be conducted to generate new functional features. However, due to the complexity of identifying all the functional features of the system, AMK3 is applied first. Part consolidation requires no relative motion, assembly access, and single material between two components; therefore, only pedal, pins, lever, right case, shaft, and D-shape pins are made as system of interest as depicted in Figure 11 a. As shown in Figure 11 b and c, functions are mapped to functional features. Due to the fact that the chosen system is only a portion of a bigger system, identification of system boundaries (SB) is primitive. In Figure 11 b, SB1 to SB6 all are mating interfaces while SB7 is for void consideration. In Figure 11 c, functions of components are decomposed into feature-level functions. For example, the hollow shaft needs to fulfill three functions: allow rotation, constrain rotation angle, and constrain DOF of torsion spring. System boundaries sometimes need to deliver functions as well such as the feature "import human material" and the feature "transfer rotation". In Figure 11 d, all necessary information is retrieved from the old design including system boundaries and functional features.

In this case study, all the features except system boundaries have the potential to be redesigned. Taking the feature "allow rotation" and the feature "transfer torque" for instance, to realize function "allow rotation", the functional entity is "a coaxial solid with the bearing". Apparently, the shaft can be in any shape beyond SB1 as shown in Figure 11 e. In terms of function "transfer torque", the functional entity is "a solid" and the functional feature is "a beam with one end in D shape". These modified functional features and the unmodified ones constitute the new functional feature set.

Function integration

Once the new functional feature set is complete, all the features in the set are checked for the possibility of function integration. If any two of them do not violate rules of "no relative motion", "single material", and "assembly access of a third part", these features are endorsed as potential candidates. Afterwards, AM-specific rules can be applied to verify if the consolidated features violate manufacturing constraints. If not, these features form a new design space. Conceptual design of the new throttle pedal is finished. It is worth mentioning that by using topology optimization to generate a reference model belongs to preliminary design to get the layout.

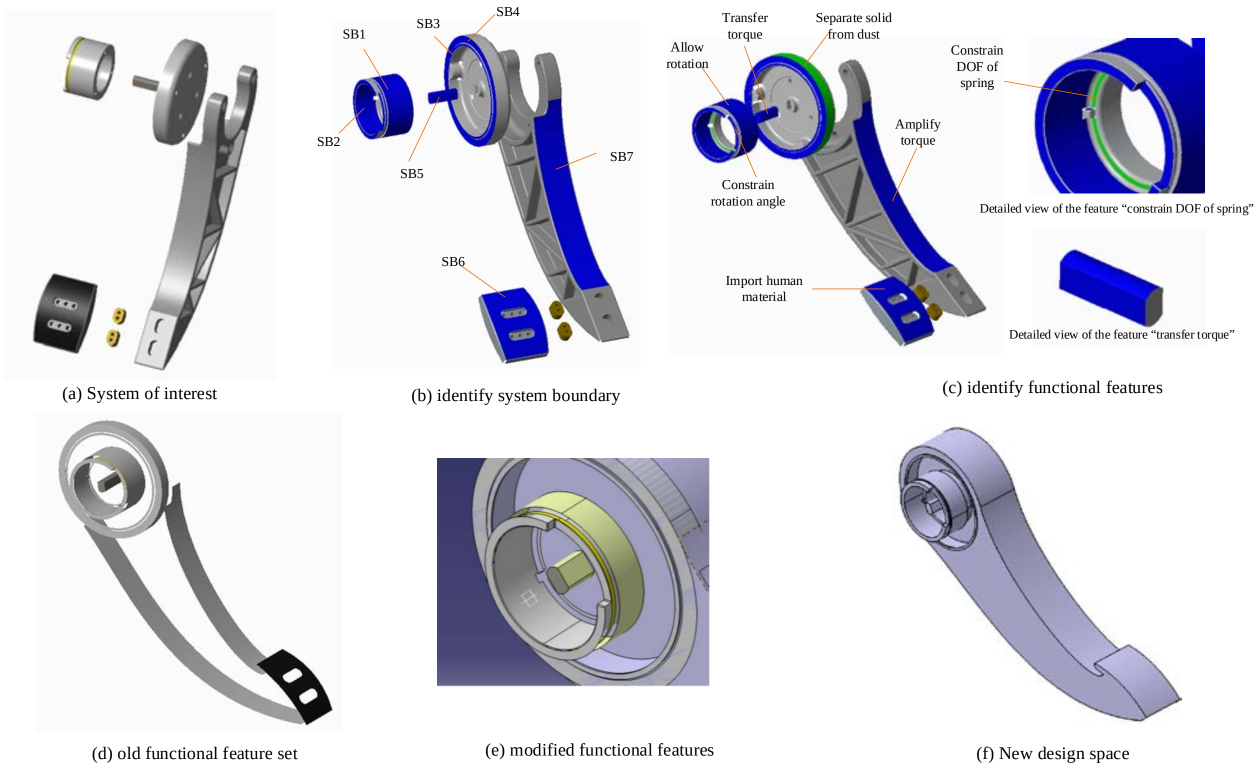


Figure 11 design synthesis and function integration process of the throttle pedal

7 Feature research

AM facilitates much more design freedom than conventional manufacturing processes did, while how to take full advantage of these capabilities have not paced up with the advances. This paper focuses on solving the problem of how to redesign an assembly at conceptual design stage in the context of AM in order to stimulate novice AM users to achieve incremental innovation. In the first place, popular design methodologies working at conceptual design stage are reviewed. These design methodologies are in different representations, but their ways of generating a design concept can be concluded as functional analysis and design synthesis. In the second place, the impact of AM-enabled design freedom on functional analysis and design synthesis are studied respectively. AM has minor effect on functional analysis process. In contrast, design synthesis stage is analyzed by using function-behavior-state functional modeling method and evidence proves that AM-enabled design freedom enriches the mapping relations between the desired behavior and the corresponding physical structures. In the third place, function-behavior-functional entity-functional feature (FBFF) design synthesis method is proposed to show how, when, and what AM knowledge should be applied in order to facilitate product innovation. In the end, FBFF method is applied in a redesign context and proved that it is able to embrace AM-enabled function integration.

In the future, two research directions need to be explored more. The first one is that conceptual design stage is so function-immersed and the unsolved issues with function description makes it difficult to encode functional information in a uniform way. The other one is how to enrich the mapping from functional entity to functional features in the proposed FBFF design synthesis method. There are two possible ways to enhance creativity. One possible way is to do analogical functional reasoning with existing products. As an example, Oregon State University managed to build a repository with more than 6000 artifacts and relate functions with various parts [21]. The other way is to establish an innovative design database serving as inspiration for new feature design [22].

ACKNOWLEDGEMENT

Financial support from the National Sciences and Engineering Research Council of Canada Discovery Grant RGPIN 436055-2013 and McGill Engineering Doctoral Award (MEDA) is acknowledged with gratitude.

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