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CUSTOMIZATION DESIGN KNOWLEDGE REPRESENTATION TO SUPPORT ADDITIVE MANUFACTURING

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ABSTRACT: The unique technologies of Additive Manufacturing (AM) have enabled new opportunities for product customization by eliminating the conventional design for manufacturing (DFM) constraints. To address the customization issues within a design for AM (DFAM) framework, this paper defines 2-step approaches: (1) representing design knowledge for customization and (2) systemically reflecting customized design factors to DFAM frameworks. As a start of the study, this paper represents design knowledge concerning customer's desired product use, customer's perceived preference, and product's functional features affecting design factors. We use Affordance Theory and Finite State Automata (FSA) to represent the design knowledge.

Key words: Affordance, Design for Customization, Design for Additive Manufacturing, Finite State Automata, Knowledge Representation

INTRODUCTION

Additive Manufacturing (AM) is a promising manufacturing technology and increasingly being used to develop parts, tools, and products beyond Rapid Prototypes (RP). The unique capabilities of AM technologies enable new opportunities for customization, through significant improvements especially in geometry freedom, lower overall manufacturing costs, and so on (Gibson et al., 2010). However, there have existed limitations of the traditional Design for Manufacturing (DFM) in customization and much of them are due to the lack of generic software tools and design methods rather than limitations of the AM related hardware (Gibson et al., 2010).

There have been many efforts to address customization issues in various industries (Moon et al., 2014). Product family design is a solution for mass customization by allowing highly differentiated products to be developed from a common platform while targeting individual products to distinct market segments (Shooter et al., 2005). Also, customizability analysis has been conducted to justify cost effectiveness of customization while concerning product variations in design and related process variations in manufacturing (Jiao & Tseng, 2004).

The motivation of this research is to develop an efficient design method for customized products that will support Design for Additive Manufacturing (DFAM). This paper mainly focuses on the development of a new representation of design knowledge for customization. The novel representation can show formal relationships between customer's product use and satisfaction levels and product functional features for design factors.

To represent customer's desired product uses and product's customized functional features, we adapt Affordance Theories (Gibson, 1979; Turvey, 1992) and embed them into state transition models. The product use state transitions are expressed using Finite State Automata (FSA) (Cassandras, 1999; Hopcroft, 2001) in the Discrete Event System (DES) point of view.

The reminder of this paper is organized as follows. Section 2 presents the new representation of design knowledge. Section 3 demonstrates an illustrative example and Section 4 gives concluding remarks.

DEVELOPING DESIGN METHODS FOR CUSTOMIZATION TO SUPPORT ADDITIVE MANUFACTURING

Design for Customization (DFC) method defines how customer's desired product use is combined into the product design scheme in representing individual customer needs and perceptual factors as shown in Figure 1. Customer needs for a product mostly come from customer's desired product uses (CA: customer action). Customer's perceived value is closed related to how much a customer prefers product's functions and design features (PR: preference) while utilizing a product as a tool to perform or support his/her activities.

Figure 1. Overall process of customized design for additive manufacturing

We introduce a new representation for product's functional features in the operational level using Affordance-based Finite State Automata (Affordance-based FSA) as in Eq. (1) which is a formal modelling method of human-involved complex system with a focus on system control and operation (Rothrock et al., 2011). The proposed model consists of tuples that represent the customer's goal-oriented desired behaviors in addition to the related product's functional features and customer's preference levels.

$$\begin{aligned} G_{comb} &= \langle S, \sum, \delta_{ext}, s_0, F, G_{atom} \rangle \\ G_{atom} &= \langle \{X, Z, W\}, \{P, Q, PR, PSA\}, \{G, D\}, Pr, j, \pi, \delta_{int}, t_{int} \rangle \end{aligned} \quad (1)$$

Where

$$\delta_{ext}: S \times \sum \rightarrow S,$$

$Pr: X_P \rightarrow P, Z_q \rightarrow \{Q, PR\}, W_{pq} \rightarrow PSA,$
 $\rho: P \rightarrow D,$
 $j: X_P \times Z_q \rightarrow W_{pq},$
 $\pi: P \times Q \times PR \times C \rightarrow PSA,$
 $\delta_{int}: \{P, Q, PR\} \times t_{int} \rightarrow \{P, Q, PR\},$
 $\Sigma:$ Set of transitions among states: set of customer actions for product use,
 $S:$ Set of states for combined system,
 $s_0:$ Initial (starting) state in the combined system,
 $F:$ Set of final states: goal of the customer-product system,
 $j::$ Juxtaposition function,
 $\delta_{ext}:$ State (external) transition function,
 $\delta_{int}:$ State (internal) transition function,
 $Pr:$ Perception predicate function,
 $\rho:$ Design parameter generation function
 $\pi:$ Possible customer action generation function,
 $X:$ Product system,
 $Z:$ Customer,
 $W:$ Customer-Product system,
 $P:$ Set of customized affordances, $P = \{p_1, p_2, \dots, p_m\},$
 $D:$ Set of design parameters, $D = \{d_1, d_2, \dots, d_m\}$
 $Q:$ Set of customer's effectivities, $Q = \{q_1, q_2, \dots, q_m\},$
 $PR:$ Set of preference levels, $PR = \{pr_1, pr_2, \dots, pr_m\},$
 $PSA:$ Set of customer's possible product use with preference level labeled,
 $C:$ Set of physical action conditions,
 $t_{sa}:$ Target customer action, $t_{sa} \in PSA$ and $t_{sa} \in \Sigma,$ and
 $t_{int}:$ Time advance function.

The proposed representation corresponds to DFC with two reasons. First, the model can represent the perceived values of product users (as preference) and functional requirements of customized features (as affordance). The state set of product use system is represented as

$$S = \{s_1, s_2, \dots, s_n\},$$

where, $s_i = \{q_i, p_i, pr_i\}, 1 \leq i \leq n < \infty,$ and

$q_i, p_i,$ and pr_i is the affordance, effectivity, and preference level in i^{th} state respectively.

As each of the affordances is well matching with customer activities, capabilities, and preferences, which is shown in the function $\pi: P \times Q \times PR \times C \rightarrow PSA$ of the representation, the affordance set represents customized functional features.

Second, by formally representing product state changes into state transition forms which is triggered by customer product uses (δ_{ext}) or time advances (δ_{int}), the new definition successfully shows state changes systemically. When a customer operates a product or when the time goes by the functions and physical states of a product are changed, which is represented as state transitions in the paper. In this way the method can not only deal with static design values but also dynamic properties of design factors ($\delta_{ext}: S \times \Sigma \rightarrow S, \delta_{int}: \{P, Q, PR\} \times t_{int} \rightarrow \{P, Q, PR\}$).

From the representation a language $L(G_{comb})$ can be defined as Eq. (2):

$$L_m(G_{comb}) := \{pa \in L(G_{comb}) : \delta_{ext}(s_0, pa) \in F\}, \quad (2)$$

Where,

$$L(G_{comb}) := \{pa \in \Sigma^* : \delta_{ext}(s_0, pa) \text{ is defined}\}.$$

The above definition assumes the extended transition function $\delta_{ext}: S \times \Sigma^* \rightarrow S$. $L_m(G_{comb})$ is a subset of $L(G_{comb})$ consisting only of the customer activities for which $\delta_{ext}(s_0, pa) \in F$ (Cassandras, 1999). These activities correspond to paths that finish at a marked state, which is a final goal in the state transition diagram of customer action and product states. The marked language $L_m(G_{comb})$ is a set of customer's desired product uses that can achieve final goals.

Here, a product that support $L_m(G_{comb})$ needs to be designed to contain corresponding affordances P_{L_m} as the product's customized functional features. These relations are expressed in the formula as shown in Eq. (3).

$$\pi^{-1}(L_m(G_{comb})) = \{P_{L_m}, Q_{L_m}, PR_{L_m}, C_{L_m}\} \quad (3)$$

The formula provides product designers with important guides in terms of designing and deploying customized functional features P_{L_m} for a product according to customer's preference PR_{L_m} . Finally, the customized affordances P_{L_m} can be categorized and matched to design parameters D . The product needs to characterize the customized affordances in its interfaces and physical designs so that the involved customers can perceive the features to achieve his/her activities goals while utilize the product.

ILLUSTRATIVE EXAMPLE

As a representative illustrative example, a simplified example is presented by a graphical representation in Figure 2. The starting point of the customer's desired activity is to conduct action A with a product. After the action A , the customer can take an action of either B or C .

Figure 2. Graphical representation of state transitions

In this case the customer can achieve his/her goal by arriving the final state c or d . Therefore the customer's desired products uses, $L_m(G_{comb})$, can be defined as $L_m(G_{comb}) = \{(0.5A \cdot 0.5B), (0.5A \cdot 0.4C)\}$ which is a set of two different customer activities with the product. According to Eq. (3), P_{L_m} , Q_{L_m} , and PR_{L_m} can be earned as follows:

$$P_{L_m} = \{(p_A p_B : A_able \cdot B_able), (p_A p_C : A_able \cdot C_able)\},$$

$$Q_{L_m} = \{(q_A q_B: \text{capability_to_A} \cdot \text{capability_to_B}), \} \text{ and } \{(q_A q_C: \text{capability_to_A} \cdot \text{capability_to_C})\},$$

$$PR_{L_m} = \{(pr_A pr_B: 0.5 + 0.5 = 1.0), (pr_A pr_C: 0.5 + 0.4 = 0.9)\}.$$

Note that the numbers attached before the actions are the customer's perceived preference levels toward the related affordances that can be referred for evaluating how well the features are customized. In this case the preference levels PR_{L_m} are earned with an assumption that the features are independent. According to the preference levels, designers can decide that features with higher values are better customized.

After designers come out with the product's customized functional features, they are able to use the information to figure out design parameters D as follows:

$$\rho(P_{L_m}, A_{AM}) = D.$$

Also note that even the function ρ is still arbitrary, this paper propose the customized design parameters need to be reconsidered with AM's manufacturability aspects: A_{AM} . A_{AM} s are the manufacturing capabilities and constraints from AM's operational characteristics which deal with parts' geometric and orientation features, process, machine, and material properties, and so on.

CONCLUDING REMARKS

This paper proposed a formal representation of design knowledge for Design for Customization (DFC) methods to support Additive Manufacturing (AM). Customer needs, which come from customer's desired product use, and product functional features were formally represented utilizing Affordance Theories while preference was adapted to deal with customer's perceived satisfaction values. The product use changes in dynamic contexts were represented by using Finite State Automata (FSA) in the view point of Discrete Event System (DES).

A further direction of this research will be to address issues in terms of matching customized affordances to design parameters in-depth in various categories and have them to intersect with Design for AM (DFAM) frameworks. Also, we anticipate addressing issues in performance evaluation of customization and efficiencies of AM processes will be required as well. While customized design factors are achieved in the proposed DFC framework, they will be affected by AM characteristics and process capabilities and constraints such as part orientation, topology optimization, and manufacturing path optimization in the DFAM point of view. It will be the level of customization that decides the valance between maximizing customer's satisfactions and manufacturing process efficiencies.

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