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USER-CENTERED DESIGN FOR ADDITIVE MANUFACTURING AS A CUSTOMIZATION STRATEGY

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ABSTRACT: As additive manufacturing (AM) has broadened design freedom significantly, conventional design theories and methodologies for customization or mass customization are challenged. This research aims at developing a user-centered design methodology for additively manufactured interactive parts that improves the level of customization. We propose a design methodology built upon the concepts of the three link chain model-based design for AM and design for customization. The proposed methodology also utilizes affordance- and preference-based finite state automata model to reflect preferable behavioral design requirements for customization in a dynamic artifact-user interaction context. The methodology deals with the design complexity increased by exploring AM-enabled design freedom in a systematic engineering design approach. Then this paper discusses the methodology’s availability in the design of additive manufactured interactive products such as prosthetic limbs.

KEYWORDS: additive manufacturing, customization, design methodology, user-centered design

1. INTRODUCTION
The unique tool-less and layer-upon-layer capability of additive manufacturing (AM) has largely alleviated manufacturing constraints and significantly broadened design freedom (Gibson, Rosen, and Stucker 2010). This AM-enabled design freedom offers new opportunities for customization by achieving significant improvements in product performance, multifunctionality, and lower overall manufacturing costs for developing customized products (Chu, Graf, and Rosen 2008). Furthermore, as AM evolves beyond rapid prototyping to the end-of-use product manufacturing, conventional customization design theories and methodologies especially life-cycle objectives oriented ones are challenged inevitably (Yang and Zhao 2015). Conventional design methodologies have drawbacks that they are not qualified to embrace the new opportunities for AM-enabled customization and consequently underline the need for a set of design principles for it.

Design for AM (DfAM) is a methodology to maximize product performance through the synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to the capabilities of AM technologies (Rosen 2014), while the level of customization is affected by the effectiveness of the AM processes and the unique capabilities of additively manufactured parts (Ko, Moon, and Hwang 2015). With a similar point view, Ko, Moon, and Otto (2015) proposed design knowledge representations supporting AM-facilitated personalization.
By utilizing the design process structure and formal knowledge representations proposed by Ko, Moon, and Otto (2015), this paper aims at proposing a new systemic design methodology for customized DfAM based on the three link chain model (3LCM) (Olson 1997)-based DfAM that has a process–structure–property–behavior relationships framework (Rosen 2007; Chu, Graf, and Rosen 2008). The proposed methodology combines behavior requirements and manufacturing constraints into an AM-enabled customization idea on interactive and functional surfaces and volumes from the conceptual level, which has been rarely involved in the prior studies, since they are only applicable in downstream design activities, i.e., detailed design phase (Yang and Zhao 2015).

2. A USER-CENTERED DESIGN METHODOLOGY FOR ADDITIVE MANUFACTURING-ENABLED CUSTOMIZATION

The proposed methodology initializes the purpose of realizing AM-enabled customization with a series of design phases as shown in Figure 1. A description of each phase is as follows.

Phase 1: Specifying customization requirements
Phase 1-1: Identifying artifact-user interaction components
Instead of using common behaviors, this paper pursues to use customized behavior parameters as inputs for 3LCM-based DfAM. To investigate the characteristics of customized behaviors, the methodology utilizes affordance- and preference-based design method. Here, affordances act as a systemic link that connects user behaviors to the physical structures originated from affordance-based design (Maier and Fadel 2009). Preferences play a role as a tool for measuring parts’ performances to indicate the level of customization.

Phase 1-1 investigates affordance, effectivity and preference in the structured framework of an artefact–user interaction model, while viewing user’s preferable behaviors with artefacts as the
outcome of the artefact–user interaction. Effectivity is user’s capability to capture the affordance’s relational opportunities for actions and conduct the actions that correspond to the matched affordance (Ko, Moon, and Otto 2015). This phase achieves a structural model of affordance-effectivity-preference as a result of it.

**Phase 1-2: Representing artifact-user state transition model**

After identifying the structured affordance-effectivity-preference relationships involved in the artifact-user interaction, Phase 1-2 analyzes dynamic properties of artifact-user state transitions and represent them using a computational modeling technique of finite state automata (FSA) (Cassandras and Lafortune 2008).

The artifact-user behaviors in product uses are dynamic. However, prior studies on AM-facilitated customization remained mostly static and rigid, while they are considered in terms of body-fitted complex components in a static situation. In the dynamic artifact-user interaction context, human-related constraints continue to fluctuate in the user’s artifact-use behaviors and reflecting them to the customization is considered significant, due to its increased design complexity increased by its dynamic characteristics. Therefore, in addition to the static body-fitting characteristics, designers have to consider the design requirements that reflect the user behavior-fitting characteristics in a dynamic context. This type of design requirements is very significant in AM-facilitated design studies, because AM’s unique capability of shape complexity, material complexity, hierarchical complexity, and functional complexity is suitable to realize the increased design complexity.

Phase 1-2 achieves a affordance-, effectivity-, and preference-based FSA model (Eq. 1) and a corresponding state transition diagram as shown in Figure 2 (Ko, Moon, and Otto 2015) as results. Ko, Moon, and Otto (2015) showed a case study of preference-labeled user behaviors in a customized interactive chair design.

\[
G = <S, \sum, \delta, s_0, F, \{X, Z, W\}, \{P, Q, PR, PPA\}, Pr, j, \pi>
\]

where,
- \(S\): a set of states
- \(\sum\): a set of transitions among states: set of user actions in the artefact use,
- \(\delta\): state Transition Function, \(S \times \sum \rightarrow S\),
- \(s_0\): initial (starting) state
- \(F\): a set of final states: goal of the artefact-user interaction
- \(X\): artefact,
- \(Z\): user,
- \(W\): artefact-user,
- \(P\): a set of affordances, \(P = \{p_1, p_2, \ldots, p_m\}\),
- \(Q\): a set of effectivities, \(Q = \{q_1, q_2, \ldots, q_m\}\),
- \(PR\): a set of preferences, \(PR = \{pr_1, pr_2, \ldots, pr_m\}\),
- \(PPA\): a set of possible actions in the artefact use with preference level labeled, \(PPA = \{ppa_1, ppa_2, \ldots, ppa_m\}\),
- \(Pr\): perception predicate function, \(X_F \rightarrow P\), \(Z_Q \rightarrow \{Q, PR\}\), \(W_P \rightarrow PPA\),
- \(j\): juxtaposition function, \(X_F \times Z_Q \rightarrow W_P\),
- \(\pi\): possible customer action generation function, \(P \times Q \times PR \times C \rightarrow PPA\),
- \(C\): a set of physical action conditions, and
- \(pa\): possible user action, \(pr \cdot pa \in PPA\) and \(pr \cdot pa \in \sum\).
Phase 1-3: Representing user behavior model in artefact use

Each actualization of user action is defined as a state transition, which means that a combination of each action represents successive user actions that are defined as user behaviors; a finite sequence of user actions.

In this phase, the user behavior is defined as a series of specific user actions. The goal is the desired states that the user arrives at after performing a series of actions with the artefact. Based on the FSA models and the state transition diagrams, a connection between the formal model and languages (Cassandras and Lafortune 2008) can be considered to address the logical relationships between the goal-oriented user behavior and the related design requirements. From the proposed formal model, all possible user behaviors from the initial product use (initial state) can be generated as a language in Eq. (2):

\[ L(G) := \{ pa \in \sum^* : \delta(s_0, pa) \text{ is defined} \} \]

where,

\[ \delta : \sum^* \times \sum^* \rightarrow \sum^* \]

\[ \sum^* = \{ \pi(p_i, q_i, p_n) \} \subseteq \sum^* \]

In the equation, \( L(G) \) represents all the directed paths that can be followed along the state transitions that start from the initial state in the model. Among the user behaviors in \( L(G) \), this paper defines another type of the user behavior using marked language (Cassandras and Lafortune 2008) as Eq. (3):

\[ L_m(G) := \{ pa \in L_m(G) : \delta(s_0, pa) \in F \} \]

As seen in Eq. (3), \( L_m(G) \) is a subset of \( L(G) \) consisting only of the user behaviors for which \( \delta(s_0, pa) \in F \). These user behaviors correspond to paths that finish at a marked state, \( F \), which is the set of final goals in the state transition diagram. Therefore, \( L_m(G) \) defines all possible user behaviors that start from the initial states and achieve the final goals in the artefact use. In terms of designing user behaviors that achieve the final goals and related design specifications, the marked language \( L_m(G) \) can be a significant concern.

Phase 2: Conducting design optimization based on design for additive manufacturing

Phase 2 applies the customized behaviors \( L_m(G) \) from Phase 1-3 to the 3LCM-based DfAM. When the process–structure–property–behavior relationships are used for a design method instead of material science, the meaning of the model remains the same but the context changes (Doubrovski, Verlinden, and Geraedts 2011). In AM-facilitated customization, designing the performance of 3LCM includes designing design requirements that support users in the artifact use behaviors, \( L_m(G) \), therefore they can provide users with preferable product uses. These requirements can be
based on the customized artifact’s behaviors such as a user’s preferable weight or strength and perceivable surface properties. The structure of the 3LCM is the physical layout that controls or affects the customized behaviors of the artefact. The structure can be at from the product level to the smaller material level (Doubrovski, Verlinden, and Geraedts 2011). Finally, processing represents a specific AM method.

While an additively manufactured part that can afford $L_{am}(G)$ needs to be designed to contain corresponding affordances, the methodology still needs to consider the design optimization processes in detail design phases. The affordances do not exist in isolation. The affordances should be interpreted as detailed design attributes that in isolation identify bounds and targets for each property represented in the affordance and preference attributes. In a seat design, for example, this interpretation will integrate the customized seat height and the width of the seat back, the elasticity of the seat components, etc. After the design requirements are specified, in terms of DfAM the design specifications incorporate AM’s process parameters such as the orientation, slicing, supports, scan speed, layer thickness, and hatch density to consider AM manufacturability that affects the level of customization (Yao, Moon, and Bi 2016).

3. DISCUSSION ON PROSTHETIC AS A CASE STUDY

The development of prosthetic sockets can potentially benefit the use in terms of cost and quality if produces using AM (Doubrovski et al. 2015). While a prosthetic leg typically consists of three components that are foot, pylon, and socket, design phases need to measure not only the 3D geometry of the residual limb, but also the walking or running behaviors that affects the behaviors of the main three components and comfort of its wearer in a dynamic product-use context. There were many prosthetic studies in terms of geometry design and behavior modeling, but in isolation. The proposed affordance- and preference-based design methodology is expected to act as a logical link between the isolated fields, therefore increase the completeness of the prosthetic designs.

4. CONCLUDING REMARKS AND FUTURE WORKS

The unique capability of AM offers new opportunities for customization. However, conventional design theories and methodologies are not qualified to embrace these new opportunities and consequently, it is required that new design principles and methodologies for AM to achieve a customized design.

In this paper, we proposed an optimization-based systematic methodology for AM-facilitated customization that is built upon the concepts of DfAM and customization. The proposed methodology is based on the 3LCM-based DfAM that has a process–structure–property–behavior relationships framework. The methodology is meaningful that it combines behavior requirements and manufacturing constraints into an AM-enabled customization idea from the conceptual level, which the previous studies lacked.

So far, the proposed methodology focuses mainly on the conceptual and preliminary design. The future work will be conducted in terms of the embodiment and detail design. For example, design representations utilized in the methodology will be extended to match the affordances to geometrical design parameters. Also, design methods will be developed for design and process selections and decision-makings to identify optimal design solutions utilizing the proposed preference attribute. The future work will be applied in designs of additive manufactured interactive products such as customized shoes, prosthetic limbs and sensor-embedded wearables.
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