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Product personalization enabled by assembly architecture and cyber physical systems

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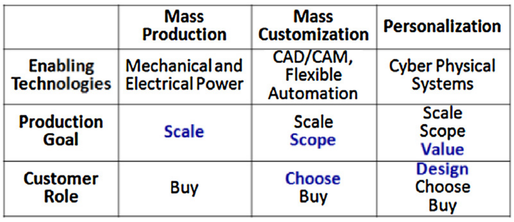
ABSTRACT

Personalization is an emerging manufacturing paradigm towards meeting diversified customer needs. This paper proposes a framework for producing personalized products efficiently. An approach for optimal mix of different module types is proposed in order to construct a proper assembly architecture. Sketch-based modeling, which facilitates easy model creation and modification by customers, is presented as a key to personalized design. A cyber physical system provides the platform for the collaborative design and co-creation of personalized products. A case study on personalized bicycles based on the proposed framework is presented. Such a framework enables open product realization through active customer participation.

1. Introduction

Several paradigms have emerged in the history of manufacturing, such as mass production and mass customization [1–3]. Each paradigm is associated with different consumer driven market dynamics and enabled by the technologies of the time. Fig. 1 provides a summary of the evolving paradigms and the enabling technologies of each industrial era. It can be observed that the emergence of a new manufacturing paradigm was always accompanied by new technological advances. For example, the invention of electrical power led to the wide use of dedicated machines and automated production systems for mass production. CAD/CAM and flexible automation systems made mass customization possible.

Today, we are at the cusp of a new industrial revolution [4]. Smart machines, people, and enterprises connected by the high speed internet will fundamentally change manufacturing. Such connected systems, called cyber physical systems (CPS) [5], will improve manufacturing quality and productivity by supporting smart manufacturing. More importantly, CPS will fundamentally transform manufacturing by enabling customer participation in product realization and supporting the collaboration of customers, suppliers and manufacturers. Personalization is emerging as a new manufacturing paradigm aiming to address the highly diversified customer needs and the strong customer desire to participate in product design and manufacturing [1,3].



	Mass Production	Mass Customization	Personalization
Enabling Technologies	Mechanical and Electrical Power	CAD/CAM, Flexible Automation	Cyber Physical Systems
Production Goal	Scale	Scale Scope	Scale Scope Value
Customer Role	Buy	Choose Buy	Design Choose Buy

Fig. 1. Manufacturing paradigms supported by enabling technologies. (Adapted from Ref. [3]).

To realize personalization, several challenges need to be addressed by developing the following key enablers [3].

Open product architecture: Personalized products will have a modular architecture allowing the integration of user designed modules together with other manufacturer designed modules [1,6]. Extensive work has been done in relevant areas, such as research on platform-based product development, product line design, and product portfolio planning [7]. However, since most existing methods deal with product architectures by considering only common and customized modules for mass customization, these methods have not been applied to product architectures with additional personalized modules. In addition, effective interface management will be a key issue to achieve compatibility of personalized modules with high design variations.

Personalization design: Customers will participate in the design of personalized modules and assemblies as amateur designers. Since available design tools and systems are for trained professional designers, new methods and interfaces need to be developed to support these amateurs in design. These methods can guide the design by customers, facilitate easy model creation and modification, and ensure close collaborations between customers and expert designers are possible [1].

Responsive CPS: CPS will support the collaboration and data sharing in distributed design and on-demand manufacturing. Cyber-enabled design tools and interfaces are essential for helping to manage the high level of freedom-of-expression while satisfying

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engineering constraints [5]. For highly varied personalized designs, new user-in-the-loop simulation tools are desired for product validation in terms of efficacy, safety, and manufacturability. Additive manufacturing (AM) technologies enable responsive realization of personalized modules with the capability of fabricating 3D objects directly from CAD models [8]. Computational tools for AM process planning are imperative for on-demand manufacturing of personalized modules.

This paper proposes new methods and tools to address these challenges, including optimization of assembly architecture, personalization design tools, and CPS for personalization. Then an integrated framework is presented for personalized production and demonstrated with a personalized bicycle case study.

2. Open assembly architecture and module differentiation

Modular architectures allow for economy of scale at the component level. Hu et al. [1] proposed an open assembly architecture consisting of common, customized and personalized modules for personalized products. Here, a major challenge is to mix the module types within a single product to satisfy customers economically. The selection of customized module variants was usually formulated as an integer programming problem for profit, share of choice, or welfare [6,9]. Personalization, however, will introduce additional complexity since the manufacturer must determine the degree of personalization offered in a given module. Berry et al. [10] developed an optimization method to determine the discrete choice of module variants and a continuous personalization parameter simultaneously. However, this method did not consider situations where the assembly architecture may involve the selection and combination of multiple attributes for a personalized module, and the complication in characterizing the intricate relationships among product functionality, cost, and specificity. Another challenge stems from interface management to accommodate design variations of personalized modules.

2.1. Optimal mix of product module types

The mix of product module types can be expressed as a hierarchical decision making process in Fig. 2. Assume a product platform consisting of m modules, where $m = 1, \ldots, M$, and each module includes l candidate variants, where $l = 1, \ldots, L_m$. Each module variant is either a non-personalized variant or a personalized variant. A module can have multiple non-personalized variants but only one personalized variant. The goal is to determine the choice-menu of module variants as well as the key parameters of personalized modules from which customers can derive their products through assembly combination of variants. Manufacturer determines the module variants offered to s market segments, where $s = 1, \ldots, S$, and x_{sml} is a binary variable whose value equals 1 when selected and 0 otherwise.

A module will be offered as either a common module with one non-personalized variant, a customized module with multiple non-personalized variants, or personalized modules with one personalized variant. Further decisions are necessary for any personalized modules. For example, a personalized bicycle may offer a handlebar with two personalized attributes: shape-tailored grips and customer-designed bar. The manufacturer should decide how to mix these attributes with economical parameters. In Fig. 2, suppose variant l is a personalized variant with p personalized attributes, where $p = 1, \ldots, P_{mlt}$. Here the choice for each personalized attribute y_{mlt} is described as a binary variable.

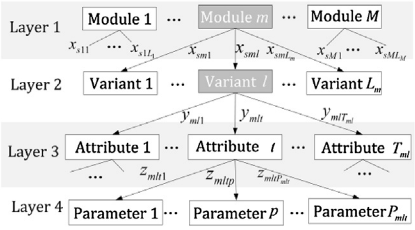

Fig. 2. Hierarchical decision making process.

Attribute parameters describe the key design and manufacturing parameters (e.g., process, material, accuracy) dominating product functionality and manufacturability, and variable z_{mltp} represents the parameter value.

The optimal assembly architecture is achieved through the tradeoff between the utility and the manufacturing cost. The manufacturer will propose an initial product portfolio with all candidate module variants. For a non-personalized variant, the utility is determined by market research and conjoint analysis. Utility function $u(e)$ will be fitted to module utility against functionality. Manufacturing cost will include variable unit cost c (related to material, labor, and operations), and fixed unit cost f (related to manufacturing system utilization). Manufacturers should determine the cost of each module variant during process development. Functionality e will be determined from knowledge or data in pilot experiments. For personalized module variants, the evaluations of utility, variable cost and functionality depend on the attribute combination and parameter values to offer. A metric called *personalization quotient* (PQ) is introduced to characterize the personalization degree of a module,

$$\xi(\mathbf{Y},\mathbf{Z}) = \sum_{t=1}^{T_{ml}} y_{mlt} w_{mlt} \sqrt{\sum_{p=1}^{P_{mlt}} r_{mltp}^2 (z_{mltp})/P_{mlt}} \tag{1}$$

Here, w_{mlt} weighs the impact of attribute t on the achievement of personalization. Variable r_{mltp} represents the personalization degree of parameter p. For a continuous attribute parameter p (e.g., manufacturing error), PQ is calculated by Eq. (2).

$$r_{mltp}(z_{mltp}) = \left(z^+_{mltp} - z_{mltp}\right) / \left(z^+_{mltp} - z^-_{mltp}\right) \tag{2}$$

where variable z_{mltp} represents the parameter value, with z^-_{mltp} and z^+_{mltp} being its lower and upper bounds, respectively. For a discrete parameter p, r_{mltp} will be evaluated according to its performance in function fulfilment. Extensive ergonomic or psychological experiments are usually needed to formulate the functionality function $e(\xi)$. The cost function will be denoted as

$$c(\mathbf{Y},\mathbf{Z}) = \sum_{t=1}^{T_{ml}} y_{mlt} f(\mathbf{Z}_{mlt}) \tag{3}$$

Here, $\mathbf{Z}_{mlt}$ is the parameter vector of attribute t, and $f(\mathbf{Z}_{mlt})$ is the cost function. Mathematically, the optimal mix of product module types is then formulated as a welfare problem with the following objective function,

$$max\left[\sum_{s=1}^{S} \sum_{m=1}^{M} \sum_{l=1}^{L_m} q_s (u_{sml} - c_{ml} - f_{ml}) x_{sml}\right] \tag{4}$$

subject to the following constraints,

$$\sum_{l=1}^{L_m} x_{sml} = 1, x_{sml} = 0 \text{ or } 1, \forall s, m \tag{5.1}$$

$$\sum_{t=1}^{T_{ml}} y_{mlt} \geq 1, y_{mlt} = 0 \text{ or } 1, \forall m, l \tag{5.2}$$

$$z^-_{mltp} \leq z_{mltp} \leq z^+_{mltp} \quad \text{for continuous } z_{mltp}, \ \forall m,\ l,\ t,\ p \tag{5.3}$$

$$z_{mltp} \in \{1, \ldots, N_p\} \text{ for discrete } z_{mltp}, \ \forall m,\ l,\ t,\ p \tag{5.4}$$

Here, u_{sml}, c_{ml}, and f_{ml} are constants for a non-personalized module. Otherwise, they will be evaluated by $u(e)$, $e(\xi)$, $\boldsymbol{\xi}(\mathbf{Y},\mathbf{Z})$, and $\mathbf{c}(\mathbf{Y},\mathbf{Z})$ jointly.

2.2. Interface management

Interface standardization is important for achieving module compatibility [11,12]. The modules of an open-architecture product should have standard mechanical, electrical and informational interfaces, which define the protocol of the module interactions to perform the designated functions. Particularly, this paper will discuss the mechanical interfaces, which can be described as the mating faces between two distinct modules [12]. It describes the shape consistence or structural compatibility on the boundary of interconnected modules.

Three critical issues are identified for effective interface management: interface standardization, interface embodiment, and interface compatibility check. Interface standardization defines the rules or specifications applying to the interface content. For mechanical interfaces, the specifications may include the geometric types and parameters of interfaces. A number of considerations are required in interface standardization, such as interface commonality across product family, industry standards, and safety issue. Interface embodiment refers to the process of interface generation or instantiation, which is often regarded as part of module design. For personalized design, customers will create the product module in a design space subject to a variety of engineering constraints including interface specifications. So, a personalized module is a composite of customer-designed parts and standardized interfaces. An interface compatibility check will validate personalized designs for each design iteration.

3. Sketch-based modeling for personalization design

We present a low-fidelity 3D modeling method by which customers can freely create 3D design forms using simple pen-based sketch inputs without the need for detailed information such as dimensions or spatial constraints. Different from the existing feature-based or freeform modeling techniques which rely heavily on the expertises and experiences of the users, the personalization design method in this paper is intended for the inexperienced customers. By leveraging users' natural ability to draw with a pen, we reduce the need for explicit training.

Fig. 3shows the general workflow of the interface. Users start by first placing a sketch plane in the 3D workspace. The outline of a shape is directly drawn on this plane, while the backend system computes a 3D geometry from it. Sketch templates for standard geometries can also be imported on the plane from a library. New shapes can be added such that its size and proportion can be directly adjusted in the context of the overall product form. Color and texture can be used for aesthetics and material properties.

Users can choose between *tubular shapes* (circular section sweeps) or *blobby shapes* (generalized extrusions), as they only require simple 2D curves for construction, while enabling a wide variety of 3D forms. *Blobby shapes* are created by drawing a closed profile curve, and extruding them using a rounded, flat, tapered, or linear function. *Tubular shapes* are defined using two rail curves, between which a circular sweep is fitted. Shape modification is allowed for users using overdrawing techniques.

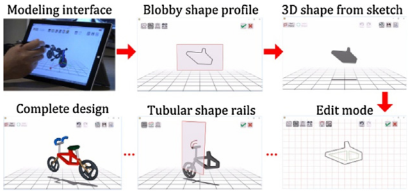

Fig. 3. General workflow of sketch-based modeling.

4. Cyber physical system

The envisioned CPS will be built upon the seamless integration of computational algorithms and physical elements. It will enable a workflow generally including personalization design, visualization of the design, product validation in terms of assembly, performance, efficacy, and safety, as well as collaboration in design, manufacturing and supply chain. This section will discuss three important elements of such a system.

4.1. Collaborative personalization design tool

Fig. 4shows an example where different personalized handlebars from other users are integrated within a specific bicycle model to generate design variants.

To support collaborations, a subsystem named *design explorer* is available for storing, viewing, and accessing designs within a concept space collectively generated by multiple users. The explorer allows for concurrent viewing of multiple designs while working on one's own design. The designs in the explorer are arranged with the most recent designs at the top. Such prioritization allows users to get a quick overview of the current state of the design concept space. In addition to creating fully personalized designs, users can also employ the explorer as a library and import existing designs (or components) for reuse or seamless integrate into their own design. Users can also import others' designs and seamlessly integrate into one's own design. To accommodate easy part substitution, the system automatically finds optimal alignment and scaling for a new part by matching its dimensions with those of the previous. Future extensions of our work could include tools to prioritize or filter designs in the explorer using text/sketch queries, functionality, materials etc.

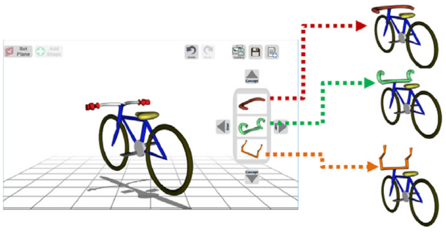

Fig. 4. Create and reuse design for personalized handlebars.

4.2. Assembly simulator

To make the user-in-the-loop assembly simulation, the assembly simulator has compatible interfaces of customer data and personalized design variants, as well as product-specific knowledge base for supporting a variety of checks on functionality, safety and assembly feasibility. Fig. 5demonstrates the assembly simulation of a personalized bike. Rider's body measurements are imported as specific customer requirements. Domain-specific knowledge organized from industrial practices, standards, and safety regulations is encoded into various functionality checks on the assembly geometry such as seat height and stand over height. The compatibility of geometric interfaces is validated by assembly feasibility checks according to the prescribed interface specifications. The assembly simulator also provides the 3D visualization of the personalized bicycle.

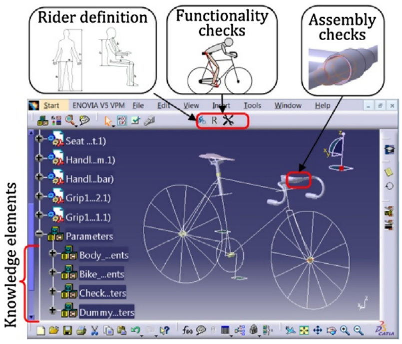

Fig. 5. Assembly simulator.

4.3. AM process planner

To support the rapid fabrication of personalized modules, we present an AM process advisor for recommending appropriate AM processes and materials for a specific design. An expandable database is built for a wide range of machines and materials on the market, which includes comprehensive information regarding process type, building size, accuracy, material property, etc. A process search starts with user inputs of the work piece size, material type, manufacturing accuracy, and other match criteria. Importantly, the AM process advisor can analyse the priorities of candidate processes according to the degree of match with the user defined preferences for manufacturing cost, part strength, part stiffness, and so on.

5. Case study

The exemplified personalized bicycle consists of multiple assembly modules (e.g., handlebar, saddle, frame, wheels). The manufacturer proposes an initial product portfolio including all the candidate module variants. Assumptions about the market characteristics are then made. Four market segments with equal population 10,000 are targeted: (1) normal riders, (2) avid riders, (3) amateur cyclists, and (4) professional cyclists. Taking the handlebar as an example, the manufacturer needs to determine the optimal choice from six non-personalized variants and one personalized variant. Table 1 lists the data from market research. Utility functions of four market segments are then formulated by fitting the discrete utility data against functionality. Two candidate personalized attributes are available: a bar with a personalized profile, and grips tailored to the rider's hands. Attribute parameters are listed in Table 2.

The optimal mix problem of module types is formulated by Eqs. (4) and (5). Optimal variable values are determined by solving this optimization problem, wherein the functionality and cost functions are given by Eqs. (6) and (7), respectively. According to the results, flat bar (preferred by normal and avid riders), drop bar (preferred by amateur cyclists), and personalized handlebar (preferred by professional cyclists) will be offered to the market. For the personalized handlebar, both a personalized bar (aluminum, accuracy = 3.0°) and personalized grips (rubber, accuracy = 1.0 mm) will be offered. In this way, we can determine the optimal mix of product module types by calculating the choice-menu for each module. Two modules (saddle and handlebar) will be allowed for personalization.

$$e(\xi) = 21.25\xi + 45.55 \tag{6}$$

$$\begin{aligned} c(Y,Z) = {} & y_1[z_{11}(2-z_{11})(-2.9z_{12}+23.6)+(z_{11}-1)(-2.9z_{12}+23.6)] \\ & + y_2[z_{21}(2-z_{21})(-6.6z_{22}+15.7)+(z_{21}-1)(-6.6z_{22}+15.7)] \\ & + 15(1-y_1)+5(1-y_2) \end{aligned} \tag{7}$$

Fig. 6shows the general workflow of the proposed cyber physical system for bicycle personalization. First, rider's anthropometric data (e.g., hand shape, height) are captured by a 3D scanner. Part of these data will be used to help the customer create a customer-specific handlebar and saddle via the personalization design tool available in a variety of computing terminals such as tablet and smart phone. Second, the personalized design will be converted into engineering model and imported into assembly simulator for design validation regarding functionality and assembly-feasibility. In particular, the rider's body measurements will be used to evaluate the functionality of personalized design towards satisfying individual customer requirements. Only the validated design can be delivered to fabricate. An AM process advisor can help a manufacturer determine the appropriate AM process and material to fabricate the personalized modules responsively. Finally, the manufactured personalized handlebar and saddle will be assembled with other common and customized modules into a personalized bicycle.

Table 1
Data for non-personalized handlebar variants.

l	u_{13l}	u_{23l}	u_{33l}	u_{43l}	c_{3l}	f_{3l}	e_{3l}
[1] Flat bar	25	25	22	19	9	5	18
[2] Riser bar	28	28	24	24	12	7	25
[3] Drop bar	32	34	40	44	20	10	45
[4] Bullhorn	32	33	37	42	18	9	42
[5] Butterfly	31	31	33	35	23	10	38
[6] Cruiser	28	26	23	20	13	6	22

Table 2
Parameters for two personalized handlebar attributes.

Attribute	Process	Material	r	Manuf. accuracy range	
				Min	Max
[1] Bar	CNC bending	[1] Al	0.8	0.2°	0.3°
		[2] Steel	0.6		
[2] Grip	Additive Manuf.	[1] Rubber	1.0	0.1 mm	1.0 mm
		[2] Plastic	0.7		

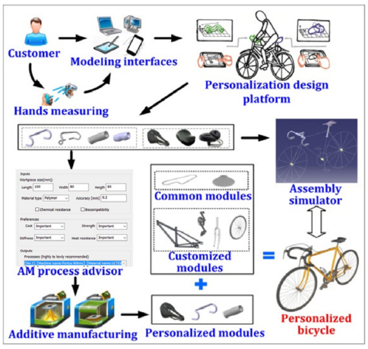

Fig. 6. Cyber physical system for bicycle personalization.

6. Conclusion

An integrated framework was proposed to support personalization and demonstrated with an example of a personalized bicycle. An open product architecture allows for the combination, mix and match of common, customized and personalized modules. The module types, personalized attributes and parameter values are determined by solving a non-linear optimization problem. A new 3D modeling interface is developed to enable customer design of personalized modules using simple pen-based sketch inputs. A cyber physical system integrates a set of computational tools with various physical machines to support personalization design and on-demand manufacturing.

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