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ON DESIGN CONCEPT VALIDATION THROUGH PROTOTYPING: CHALLENGES AND OPPORTUNITIES

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ABSTRACT

Prototyping is widely used as a means to illustrate and exemplify design requirements and intents and interact with designers and users. This paper aims to review the role and function of prototyping particularly in design concept validation. It reveals that prototypes offer interactive communication of concepts where the sense and perception of design concept intended by users is of primary importance. Our review also illustrates the rising trend from a physical prototyping approach to a more digital or mixed prototyping means. Accordingly, product attributes, whose values are presented by a prototype in conceptual design, are categorized into two major groups, namely sensed attributes and experienced attributes. The values of sensed attributes are directly received by human physiological senses and the values of experienced attributes are perceived through man-product\service interaction. Finally, by summarizing many existing research efforts including the communication of attribute values, this paper presents several major challenges in design concept validation through prototyping. It opens up a discussion regarding potential opportunities associated in this direction.

Keywords: conceptual design, concept validation, prototyping, communication, uncertainty

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1 INTRODUCTION

Competitive atmosphere of global market and rapid changes in technology, customer requirements and their expectations make shortening time to market, customization and personalization the key objectives in product development missions (Jiao and Chen, 2006, Maropoulos and Ceglarek, 2010, Nee et al., 2012, Zheng et al., 2008). These pressing challenges have motivated extensive researches and developments in industries. Decisions made at early stages of design play important roles in development time and product quality, cost and customizability (Stark et al., 2010b). However, arriving at decisions is very hard due to uncertainties and ambiguities flowing in these stages.

Validation has become primary of importance at these stages especially at conceptual design (Bordegoni et al., 2006, Maropoulos and Ceglarek, 2010). It leads to avoiding or resolving errors before being spread across several aspects of design. Prototyping has been widely employed for validation at conceptual design. Prototype as transmitter presents values of concepts to customers. One of the most important issues in validation through prototyping is that customers truly perceive concept values when they are interacting with prototypes. It is the necessary condition for reliability of customer feedback. This paper mainly focuses on concept validation through prototyping and specifically deals with physical products. It presents several pressing challenges and offers great opportunities in this topic.

The paper is organized as follows. First, Section 2 introduces a framework for validation tasks at conceptual design and states the scope of the paper. Then, technical approaches in concept validation through prototyping are reviewed in section 3. Next, Section 4 presents several challenges and opens up various opportunities for concept validation topic. Section 5 concludes the paper.

2 VALIDATION IN CONCEPTUAL DESIGN

A framework for early stages of design is given in Figure 1. These stages are essential in product design since most of important decisions are made at these stages (Dani and Gadh, 1997, Whitney, 1990). They are iterative due to incomplete information and ambiguities flowing in them. At needs identification, customer statements are vague, ambiguous and incomplete especially because of linguistic nature of communication tools. Qualitative, abstractive and subjective properties of language and verbal information put many uncertainties in design. Extracting specific information from this vague information requires many hours of discussion within design group and even recalling customers. At conceptual design, product concepts are generated and evaluated in order to span a space of possible concepts and choose the most promising concept(s) as the best one(s) for development (Whitney, 1990). Conceptualization is taken place for product (sets) and for features (alternatives). Alternatives can also be a new set and contain several attributes (analysis). At the end, they can be combined to generate new concepts (synthesis). Alternatives, in the context of this paper, are the concepts generated for fulfilling a need or a group of needs.

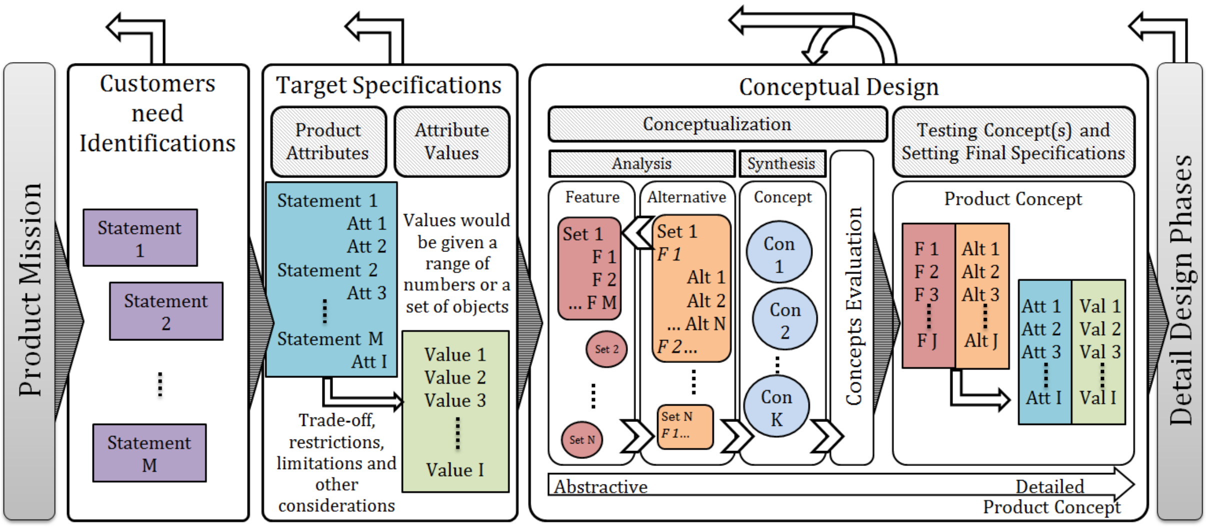

Figure 1. The framework for early stages of design

Ambiguities and uncertainties make validation as primary of important tasks at these stages. Figure 2 proposes a framework for validation at conceptual design. The concept validation process has three stages to effectively reduce ambiguity in design by engaging customers. A concept can be validated by designers (internal validation) and customers (external validation) and the difference is in the datum point of evaluations. Internal validation process is to ensure that a concept fulfills specifications intended uses, whereas, external process is to ensure that a concept fulfills its intended uses (Chen et al., 2008) or customer needs (Shabi and Reich, 2012). The former is internal since the customers are not directly involved in the process and the latter is external since they are directly involved. The internal concept validation is reliable providing that the mapping model is valid. The external concept validation is essential and necessary since it is hard to ensure that captured customer needs are complete and correct and the mapping model is valid. The scope of this paper is the external concept validation, and the paper aims to show the critical spots and the current researches on them.

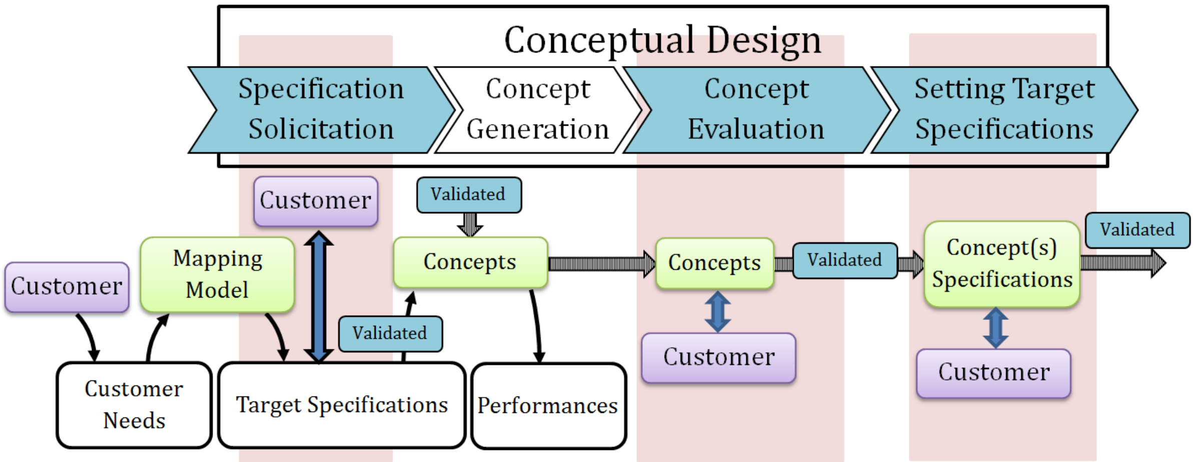

Figure 2. The framework for validation at earlier conceptual design

Sargent (1994) doubt that “In principle there is no way that a potential solution can be assumed to be valid. There must always be a design analysis stage in which a good idea is evaluated and checked”. Although it is generally accepted, a concept can be validated to some extent. This requires tools to truly communicate values of concept with designers and customers.

Figure 3 shows the process of communication in which values are transmitted to customers through a concept in an environment. Customer response would target the concept itself or the values. This paper aims to focus on the latter one. These values are usually altered when customer is experiencing real products; customer feedbacks try to push some alterations and adjustments into the process of design and development especially into specifications derived from their needs. In other words, a big part of customer feedback goes to the ‘what’. Then, to validate a concept, a transmitter should truly present values of concept to customer. This causes that various errors and uncertainties to be resolved earlier in design process and before being spread across various aspects of design.

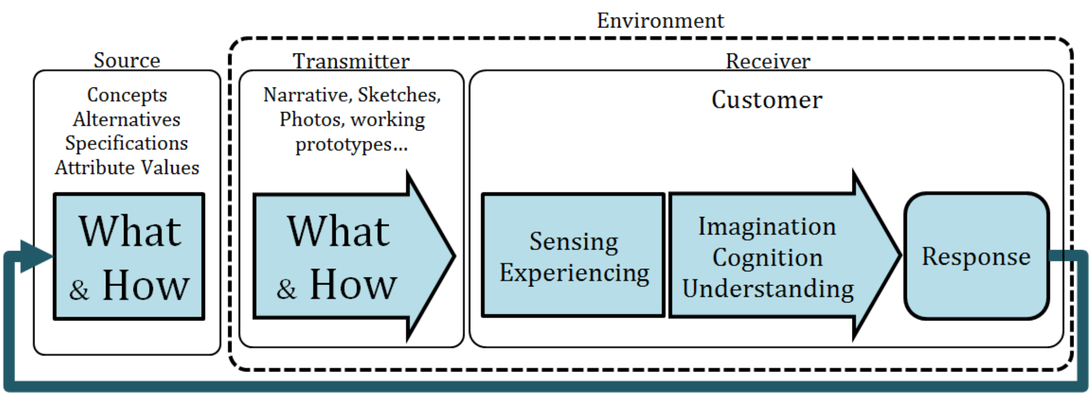

Figure 3. The Communication framework in concept presentation

3 CONCEPT VALIDATION THROUGH PROTOTYPING

Concept validation is inherent in activities of conceptual design (Maropoulos and Ceglarek, 2010). This evaluation process is both quantitative and qualitative (Gironimo et al., 2006, Maropoulos and Ceglarek, 2010). It includes inspections and measurement techniques and product-designer and product-customer interaction techniques. These techniques examine concepts and extract users' psychological profile and mood reactions (Gironimo et al., 2006). The first step to validate a concept is to present it truly. Broadly, prototyping (prototype as transmitter of values) is being used in validation activities. As a great advantage, they lead to making necessary refinements on concept by finding and correcting errors and including emotional values and unexpressed expectations of customers. This section reviews prototyping techniques employed to communicate values of concepts. Prototypes are categorized into three categories, namely physical, virtual and mixed prototypes. First, impacts of fidelity of prototypes on concept validation tasks are discussed.

3.1 Concept validation and fidelity of prototype

A prototype can be built within a range of fidelity. Virzi et al. (1996) and Sauer et al. (2010) proposed physical similarities, depth of function, breadth of functions and similarity of interaction as four dimensions of fidelity. The level of fidelity shows how much a prototype is different from physical realization of concept in each dimension. A prototype with very high level of fidelity consumes time and money, and one with very low level of fidelity would cause to invalid results. Anyway, low-level of fidelity in prototyping is widespread in industries because they are low cost and available in a short period of time (Sauer et al., 2008). Sauer and Sonderegger (2009) reported that in the majority of studies, prototypes with reduced fidelity provide equivalent results to their corresponding product in validation process. However, it depends on the attributes (Figure 1) whose values are communicated. Moreover, in some cases, a different object, which possesses the same value with a product for some attributes, would be used instead (Crilly et al., 2004, Klink and Athaide, 2006, Li et al., 2003, Stark et al., 2010a). These imply that no matter how a value is presented, it is truly received and perceived by users (Li et al., 2003, van den Hende et al., 2007). One of the most important steps in prototyping is to validate the prototype.

3.2 Concept validation through physical prototyping

In the last two decades, an innovative technology in the domain of physical prototyping were developed called rapid prototyping (RP). It speeds process of product development by enabling form-fit analysis, visual inspection and ergonomic evaluation at early stages of design (Choi and Chan, 2004, Yan and Gu, 1996). The great advantage of physical prototyping is that the communication process is very interactive. However, major limitations are that physical prototyping is costly and time consuming (Bordegoni et al., 2006, Maropoulos and Ceglarek, 2010, Nee et al., 2012, Yan and Gu, 1996). Generally, these limitations postpone making costly physical prototypes to the later stages of concept testing. Before that, the task would be done through presenting less expensive 2D or 3D paper prototypes, card sorting (Slegers and Donoso, 2012) and verbal statements (van den Hende et al., 2007). They are based on first impression of concepts and stimulation of customer's imagination, though low level of fidelity and interaction are their major shortcomings. They are mostly used for communicating attribute values such as color (Lai et al., 2006, Zuyao and Yuan, 2009), form (Sauer et al., 2010, Yannou and Petiot, 2005), color and from (Lai et al., 2006), usability (Sauer et al., 2010, Sauer and Sonderegger, 2009, Slegers and Donoso, 2012) and usability, form and dimension (Säde et al., 1998, Sauer et al., 2010). Figure 4 graphically illustrates the attributes and the physical prototypes used for them. Majority of the studies show that paper prototyping and its combination with other techniques such as card sorting and narrative have great influences on reduction of ambiguities at early stages of design. However, as the industries trend indicates, the tendency of reducing costly and time consuming physical prototyping and low fidelity level of prototypes at conceptual design lead to shifting interests of industries from physical prototyping to digital prototyping.

3.3 Concept validation through digital prototyping

Digital prototyping have become very popular to transmit values of concepts to design group and customers. It enables simulating objects and testing their functionality, form-and-fit and ergonomic aspects in a virtual environment before the object is physically realized (Choi and Chan, 2004, Ma et al., 2004). This gives design groups a great opportunity of visualization and anticipation of several aspects of concepts with less reliance on costly physical prototypes. This needs validated digital modeling tools to simulate virtual objects. Advantageously, digital prototypes can be modified easily and simulation can be done several times on one prototype. Additionally, digital prototyping enables communication and modification of concepts through the internet (Gadh and Sonthi, 1998, Kan et al., 2001). This brings many advantages in design process.

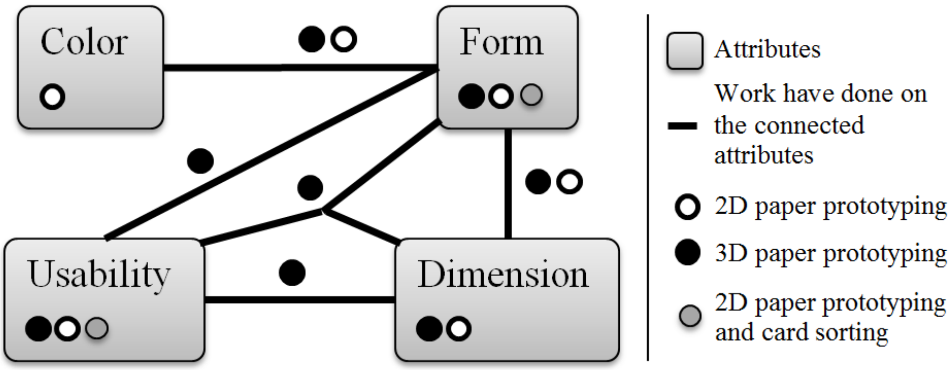

Figure 4. Attributes mostly presented through physical prototyping

Digital modeling has been extensively used for verification and validation. Digital mock-up or in some literature 'virtual prototype' is being widely used to mimic some physical characteristics of products through embedded computational codes validated and certified for that purposes. They can effectively and objectively find the errors in a design before the first physical prototype is built (Beevis and Denis, 1992). In the last two decades, computer aided design (CAD) systems were offered to communicate attributes values which can be presented through visualization, e.g. form (Corbo et al., 2004), form and color (Tsai et al., 2006), form, material and color (Fontana et al., 2005), form, color and dimension (Lee and Chung, 2008, Lee and Chung, 2005). However, they still suffer from low level of interaction (Dani and Gadh, 1997, Stark et al., 2010a, Stark et al., 2010b).

Three dimensional (3D) digital mock-up using virtual reality (VR) and augmented reality (AR) enables creating, modifying, manipulating and communicating the concepts in a more interactive way. Virtual environment (VE) provides users with realistic rendering, stereo views and sound. Li et al. (2003) empirically tested effects of 3D product visualization on presenting physical aspects of products and found that virtual experience is more effective in presenting products value than typical visual presentations. They are very useful in presenting values of attributes such as color and material (Kim and Lee, 2011, Tseng et al., 2010), form, color and material (Huang et al., 2012, emercedesbenz, 2006), form and texture (Wenfeng et al., 2004), and usability (Bruno and Muzzupappa, 2010). The interactive devices were shifted from 2D mouse to 3D mouse, joystick and pen, hand and finger gestures and voice recognizing devices. In spite of interactive communication and immersive environment, the communication of these tools is limited to seeing and hearing. Karaseitanidis et al. (2006) investigated and evaluated roles of VE in many applications such as design review, and visualization and simulation. In one of their case studies, they evaluated use of VE in subjective evaluation of car models. They found that VE is very effective on productivity, product quality, speed to market and collaboration in design applications. The same results were obtained by (Cobb et al., 1995) in investigating roles of VR in manufacturing companies in UK.

Haptic devices are employed to add sensation of touch and physical interactions. They have been widely used in many validation tasks especially in user interface design (Bordegoni et al., 2006, Clark, 2012, Gironimo et al., 2006, Pouliquen et al., 2007). They are also utilized as input devise for creation and modification of design. Up until now, VR and AR have been accompanied by haptic devices in various aspects of product design and testing. Figure 5 graphically summarizes the attributes and the tools used for communicating the attributes values in digital domain.

3.4 Concept validation through mixed prototyping

Mixed prototypes use the beneficial features of virtual and physical prototypes to offer less expensive prototypes than physical prototypes and more interactive prototypes than digital prototypes in an AR (mixed) environment. Park et al. (2009) proposed an AR-based system to enable users to interact with interface of a physically prototyped digital handheld device. The physical prototype presents the form and dimensions of the device. The user can interact with the interface through digital scenes projected on the prototype, in an AR environment. Park (2008) proposed an AR system to perform interactive modification of user interface. It supports the modification of shapes, color and texture of objects. Real re-formable mock-ups were used in this study. Barbieri et al. (2012) used functional physical prototype and AR for evaluation of interface design in home appliances. A study was performed on a washing machine. Figure 5 shows these attributes and the employed tools.

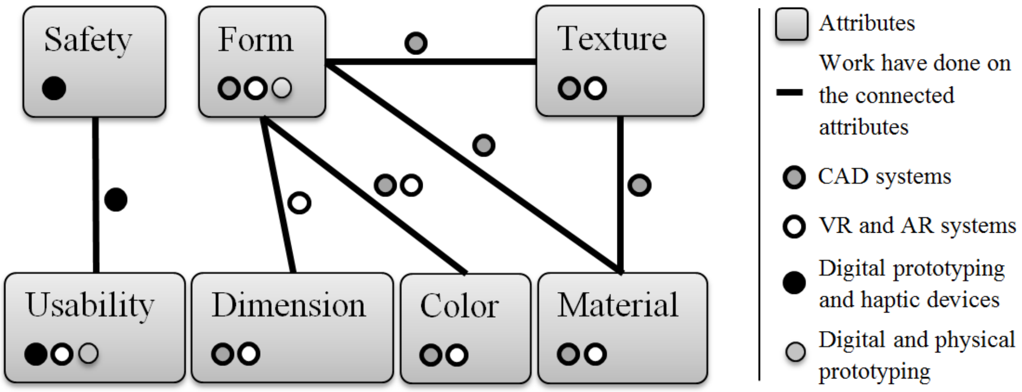

Figure 5. Attributes mostly presented through digital and mixed prototyping

4 CHALLENGES AND OPPORTUNITIES

In concept validation, truly presenting values of concepts to customers is one of the most important issues. Concepts possess values assigned to attributes. Referring to the review given in the previous section, values can be received by sensing and experiencing. Figure 6 shows some of these attributes and the amount of research done on them. In sensing process, values of attributes are received by the physiological senses of human and are immediately available to him. In this process, the consideration is on the aspects of design sensed directly through vision, touch, hearing, taste and smell. In experiencing, more interaction with design is required in order that user recognizes values. In some cases, due to tight time of design and development processes, understanding through experiences which require long time are communicated by narrative and numbers, e.g. the product is durable for 5 years. However, understanding of attribute values through short term experiences can be done by running the experiments. Psychological perceptions of the values are not considered in this paper.

Figure 6 graphically shows some challenges and opportunities in presenting attribute values. They are described and listed below.

Challenge 1-3: In communication of geometry, form, and shape,

- Rendering in virtual environment and surface finishing in physical prototyping play essential roles in communicating the values presented by shape. Shape carries many aesthetic values. However, the higher rendering accuracy and the higher surface finishing accuracy are costly and time consuming.
- Observing customer behaviors shows that they wish to experience the shape of products by themselves. In digital prototyping, an interface that gives customers the opportunity to manipulate the digital object to explore its shape characteristics is challenging. Usually this is done through multimedia systems in which users have no freedom to freely select the viewpoint.
- Communication of shape in multimedia systems is done with respect to some specific points and can be done in 360 degrees of view in CAD systems. However, the perspective view is set with respect to specific points not the position of observer's eyes. An interface, which can set the perspective view based on the line of sight, would be challenging in communicating of the shape. This is also critical in presenting dimensions.

Challenge 4-5: In presenting dimensions of objects,

- Position, scale and perspective views of virtual objects, in 3D environment need further improvements in order that the dimension is truly sensed.
- Known size objects or real scenes are being augmented in the communication environment to give a feeling of size. However, the comparison is being drawn with respect to the scaled scenes and in some cases the reference objects should be available to make a reliable comparison.

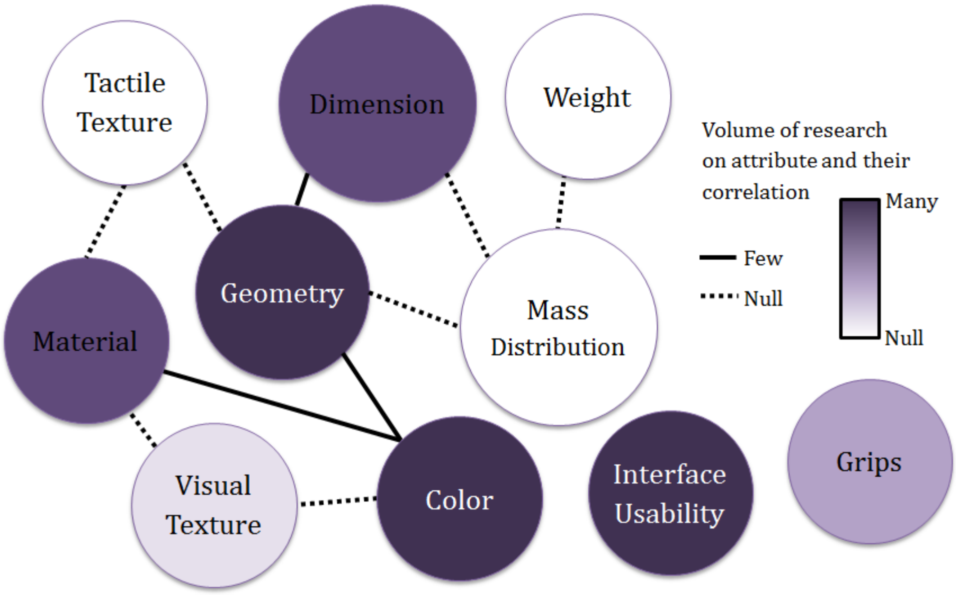

Figure 6. Attributes and the amount of research done on them

Challenge 6-7: Color is one of the most technically-challenging attributes in presenting, since it is highly correlated with other attributes such as form, material, and lighting system of the communication environment.

- A color can be differently perceived on different materials or on different textures. It is very important that the color on prototype possess the characteristics of the color on the real product. This validation process would be very challenging when color plays important role among the attributes of a product.
- Coating materials with the same colors reflect illumination in different ways. This is the other issue in communicating color getting worth under different conditions of lighting.

Challenge 8: Weight of product and more importantly its mass distribution

- These attributes are significantly critical in handheld devices. Customers mostly have strong wish to experience the weight of products. To our knowledge, no technical work has been done on this topic. The required refinements and modifications are being detected from user experience of real product and are considered in the next generation or version of the product. Mass distribution is highly in correlation with the shape and dimensions of the product. Shifting this feedback loop to the earlier stages of design is a great challenge.

Challenge 9: Surfaces and their characteristics

- Prototyping the surfaces and their properties such as roughness is the other pressing challenge. It requires expensive computing in virtual prototyping and its integration with sensation of touch requires sophisticated haptic devices. In physical prototyping it is costly and time consuming especially when higher degree of fidelity is required.

Many opportunities have been found as follows:

Opportunity 1-2: Weight and mass distribution

- Weight of a product and its distribution play an important role in customer experience and feelings about products, especially handheld ones. Typically, these values are presented by the product and the feedback loop is closed after development process. A physical prototyping technique or a haptic device, which can communicate the weight of a product or its mass distribution, shifts this feedback loop to the earlier stages of design.
- Mass distribution is highly correlated with dimension and form. It is important that these values to be communicated simultaneously to give the user an experience close to his experience through interacting with the real product. A breakthrough physical prototyping technique or VR system accompanied by haptic device would be two alternatives.

Opportunity 3-5: Color, texture and material

- A model of colors on different materials in digital domain is highly demanded. The model should possess the realistic characteristics of color such as hue, amount of saturation and intensity and the reflection properties on different material.

- Different textures describe different sensations of touch. Texture is highly correlated with material of product. These attributes values can be also conveyed through visualization to some extent. A system that can visualize these values and accompany it with sensation of touch would have a great future in industries manufacturing products such as mobile phones and laptops.
- A model that possesses the characteristics of coating materials and colors under lighting conditions in digital domain has great potential in industry.

5 CONCLUSION

This paper reviews concept validation and proposes a framework for validation in conceptual design. The framework helps designers to better understand customer needs and reduce ambiguity in design by engaging customers in conceptual design. Communication of concepts with customers is the first step to validate a concept. It is of primary importance that the presentation is done in a way that customer truly perceives and understands values of concept. This is the necessary condition to have a valid customer response.

This paper reviews role of physical, digital and mixed prototyping in validation tasks. Prototypes have been extensively employed as transmitters in concept design and validation tasks by several industrial sectors. Physical prototyping is costly and time consuming, though it offers interactive user-concept communication. Virtual prototyping suffers from lack of interaction, although it is less expensive, easy to be configured and changed. Moreover, results are often immediately available after each simulation run. The current concept validation trend shows industries interests have changed from physical prototyping to virtual prototyping. Virtual prototyping significantly decreases time to market and cost of product design and development process. Virtual testing eliminates redundancy in test process, reduces total number of physical prototypes and helps concept optimization. Mixed prototyping is proposed to offer the benefits of both physical and virtual prototyping. It is widely used for testing usability and appearance of interfaces.

Technical works on attributes are discussed. The paper reviews the attributes and the tools used for prototyping them. It reveals the amount of research done on the attributes and illustrates several major challenges and opens up some possible opportunities in this direction.

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