INTERNATIONAL DESIGN CONFERENCE - DESIGN 2006
Dubrovnik - Croatia, May 15 - 18, 2006.

DESIGN 2006

VISUAL SENSITIVITY: COMMUNICATING POOR QUALITY

K. Forslund, A. Dagman and R. Söderberg

Keywords: visual sensitivity, visual quality appearance, robust design, geometrical variation

1. Introduction

The V*isual Quality Appearance* (VQA) is defined as the impression a product conveys to a customer visually when observing it [Wickman 2005]. On assembled products, visually perceived deviations from the nominal shapes, locations and orientations of parts can have negative impacts on the VQA [Dagman 2005]. Once produced, no products are nominal, which means that all dimensions are subject to some variation. What deviations that can be allowed on an assembled product without having extensive negative impacts on the VQA depends on the *visual sensitivity* of the design concept. Visual sensitivity has been defined as a product's ability to visually amplify or suppress the lack of quality that could be visually perceived by a customer, due to geometrical variation [Wickman 2005].
Increased customer awareness of the visual appearances of consumer products has made it important for producers to develop products with a high VQA, regarding geometrical quality. Controlling the effects of geometrical variation can however be costly and time-consuming. If issues that will have negative effects on the VQA can be discovered early in the product development process, they are easier and less costly to solve in comparison to if they are discovered later on in the process. Since visual sensitivity relates only to how the effects of variation are conveyed to the customer, we consider visual sensitivity a separate product characteristic determined once the styling of a product is set. The VQA will however depend on the visual sensitivity of the styling concept combined with the final product variation (Figure 1). Tools that visualize the non-nominal geometry, in order to virtually evaluate VQA aspects of variation, have been presented by [Wickman 2005] and [Maxfield, et al. 2000]. However, these tools require that the design base has been founded to the extent that computer aided tolerancing tools can be used in order to simulate the final product variation. Also, they do not necessarily involve an understanding of the mechanisms that make certain concepts more visually sensitive than others.

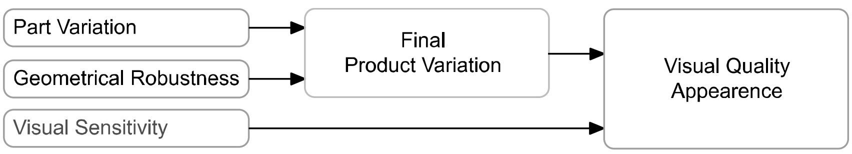

Figure 1. VQA contributors

1.1 Scope of the paper

In this paper, we present and discuss visual sensitivity as a product property. Furthermore, we will regard visual sensitivity as the extent to which the nominal geometry of a product is communicated to an observer. The concept of *visual constraints* is introduced, as a means for describing how a product conveys information on its nominal geometry. We will also present a model exemplifying different parameters that influence the probability of information on the nominal geometry reaching an observer.

2. Geometrical variation and robustness

Part variation, along with the geometrical robustness of the design concept, decides the geometrical variation affecting a manufactured product. Part variation is a result of variation in the manufacturing process of each individual part, and assembly variation is added when parts are assembled together. The geometrical robustness of the design concept will decide whether the assembly variation is suppressed or amplified as a result of the assembly architecture and the locator positioning. As seen in figure 1, visual sensitivity depends on neither the geometrical robustness nor the part variation. Rather, it is a separate product characteristic, influencing the correlation between the physical output variation and the perceived output variation. Thus, the visual sensitivity of a product can be evaluated, regardless of its risk of being affected by high output variation.

In the automotive industry, the relationships between different visible parts of the automobile's interior and exterior are critical for the overall VQA of the product. These relations are mainly analysed by two measuring directions, gap and flush, which are expected to be small, parallel and equal (Figure 2). In [Wickman 2005], a tool was developed in order to virtually evaluate the VQA of split-lines. In [Dagman 2005], the most visually and geometrically robust way of dividing a geometrical form with given locating schemes was evaluated. Form division, creating spatial relations, shall be performed with the intent to fulfil both aesthetical and functional requirements.

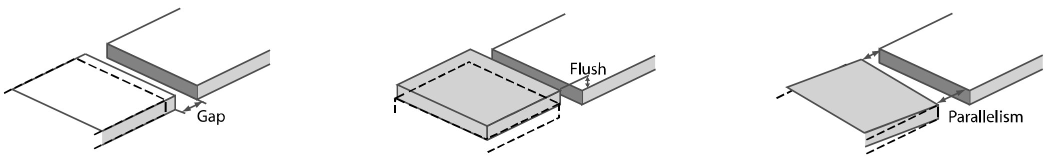

Figure 2. Gap, flush and parallelism

3. Conveying information on the nominal geometry

In the automotive industry, VQA aspects of geometry assurance have been dealt with by focusing on the sizes and shapes of the split-lines between parts. When striving to find the mechanisms that make the visual sensitivity of different split-lines or different design concepts differ, a terminology that extends beyond these measuring directions is proposed. The terminology is intended to be applicable to a wider range of industrial products. The communicative functions of exterior geometry are often referred to as aesthetic requirements. Although the current nominal product appearances are a consequence of which aesthetic ideals prevail, we will not consider the VQA purely an aesthetic issue. Instead, the insight that a product is affected by geometrical deviations is in focus, since it in itself is suggested as having a negative influence on the VQA. It is also assumed that if the nominal geometry of a product is clearly communicated, very small deviations will be brought to attention. If, on the other hand, a product or a part of a product will look nominal although it suffers from small manufacturing variation, the customer will not know that deviations occur.

3.1 Design as a process of communication

Product design has been described as a process of communication between a producer and a consumer [Crilly, et al. 2004, Monö 1997]. The customer response depends on how the design message intended by the producer is encoded into a physical product, transmitted across a channel (the physical environment), decoded by the senses (vision) and then responded to by the consumer (Figure 3).

Adopting this model in order to describe visual sensitivity, it first depends on how the product, after being disturbed by manufacturing variation, conveys information on the intended appearance (the nominal geometry), which can be compared to the actual appearance. Secondly, this information may be lost when passing through the subsequent stages of the communication process. As a consequence, the customer may fail to perceive the cues that indicate that geometrical deviations occur. In order to describe the first condition, the concept of visual constraints is introduced.

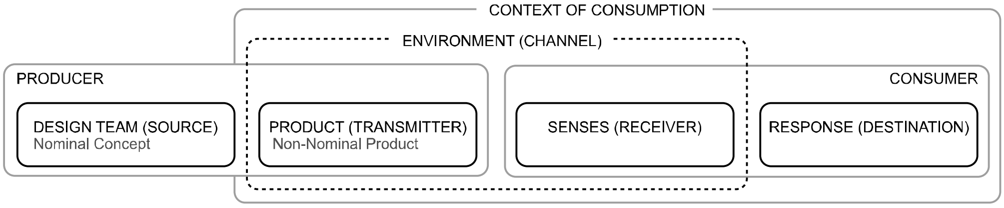

Figure 3. Design as a process of communication, based on [Crilly, et al. 2004]

3.2 Visual constraints

If there were no common expectations regarding how products are supposed to appear, it would be impossible for an observer to visually recognize geometrical deviations. Conditions such as regularity, symmetry and continuity are general elements of the manner in which objects are designed. As a result, a person encountering a new product is likely to believe that they were intended. The appearance of a product is composed of form elements such as lines, curves and surfaces that are in a spatial relation to one another. Variation that propagates through an assembled product can cause the relationships between form elements to differ from what is expected. A number of visual cues limit the way in which form elements can move or change form without causing visible conditions such as irregularity, asymmetry or discontinuity. These cues reveal the intended geometry and are referred to as visual constraints.

The term *form element*, used in [Warell 2001], relates to the external surfaces of a design. It is described as "a form 'unit', a constituent element of a physical, visuo-spacial form". Though form elements can be found on all levels of a product, the term will here signify a single edge or surface on one part, where edges can be generated by sharp edges on the geometry or by the part contours. As illustrated in figure 4, visual constraints can be found on four levels of a product. Single form elements can be visually constrained if they can be considered as predictable. Predictable single form elements can be straight lines, circular holes or flat planes, whereas unpredictable form elements can be R^3 curves or sculptured surfaces. For form elements on the same part, having an *intrapart relationship*, the visual constraints can, for instance, be parallelism or symmetry. While the first two categories of constraints are only violated as a result of part variation, the constraints on form elements on different parts can be violated due to both part and assembly variation. At this level, the relationships between adjacent parts, referred to as *interpart relationships*, are studied and the term *split-line segment* is used to denote the relationship between two different adjacent parts. Here, the constraints on surface and curve continuity (i.e. C1 continuity or tangent alignment) are added. One effect that can also arise due to assembly variation is that underlying parts or surfaces of the exterior parts not intended to be visible are exposed. The final level on which visual constraints can be found is the *whole product level*, where for instance the distances between parts in different areas of the product can be expected to be consistent.

3.3 Spatial interdependencies between form elements

For the visual sensitivity of a design concept, the interdependencies between the form elements placed on the same parts of the product are of relevance. When the assembled parts are rigid, the form elements on a part will be affected equally as the position of the part is disturbed. Therefore, several cues that indicate that specific movement might be present. How form elements are interdependent can also be studied on a more complex level, where the entire assembly architecture needs to be taken into account. If the assembled parts are compliant, the interdependencies between form elements are also difficult to predict. If visual sensitivity is to be studied without detail knowledge of, or analysis data on, how variation propagates through a complex or compliant assembly, two different approaches can be used:

- Part and assembly variation is studied, involving the possibility that parts are compliant. Therefore, interdependencies between form elements are considered to be absent, except for the evident connections between curves and surfaces on the same part.
- Parts are considered to be rigid and nominal, and form elements on the same part are considered interdependent.

Parts **Form elements**		**Assemblies** **Split-Line segments**	
Separate form elements	Intrapart relationships	Interpart relationships	Whole product level
Straightness Circularity Flatness Cylindrity Conicity Sphericity Profile	Parallellism Perpendicularity Distance Regularity Symmetry	Parallelism Perpendicularity Distance Regularity Surface Continuity Curvature Continuity See Through	Symmetry Consistency

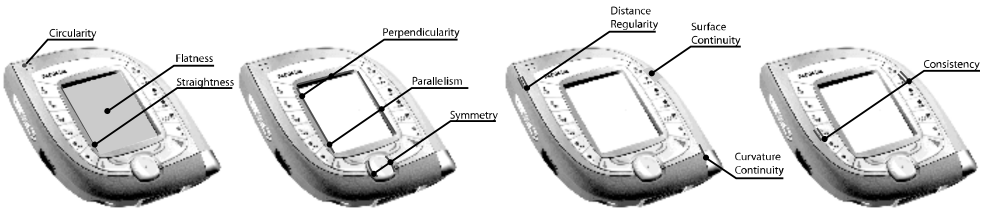

Figure 4. Categories of visual constraints found on Nokia 7600 (reprinted with permission from Nokia Corporation)

Visual constraints on four levels have been described. However, main focus will be placed on the interpart relationships. Controlling geometrical variation is made particularly difficult when assembly variation is involved, since variation of the individual parts is summed up and aspects of continuity need consideration. In order to further describe aspects of visual sensitivity, split-lines on automobiles will serve as examples.

3.4 A degree of freedom perspective to visual constraints

A comparison of how different split-line segments can be visually constrained is illustrated in figure 5, where parts are assumed to be rigid and nominal. Movement due to assembly variation is represented by translation along, or rotation around, the axes of an orthogonal coordinate system that, for simplification, is positioned so that the x-axis is aligned with the direction of the split-line. In both examples, the split-line segments require surface continuity and a regular distance between the parts. In B, the involved form elements can be simplified as straight lines and locally flat surfaces. In A, angled curves are present, and the geometry is locally a tabular surface. Curve continuity is an additional constraint in A, since two sharp curves are generated by the two visible edges. By the split-line, the tangents to these curves are however parallell to the y-axis.

The present visual constraints are listed in the figure, where violation of a visual constraint is marked with an “X”. In example B, there are degrees of freedom in which disturbances will have limited effects. For instance, the Z-translation and the X-rotation are only made visible by the surface discontinuity, while the distance between the parts is still regular. The disadvantages in A can be traced to the facts that curves cross the split-line and that the split-line is placed on an angled geometry. Though it could be assumed that example B would be less visually sensitive since fewer visual constraints are violated, the clarity of the constraints also determines the visual sensitivity. It might, for instance, be easier to distinguish an irregular distance between two straight lines than one between two curves.

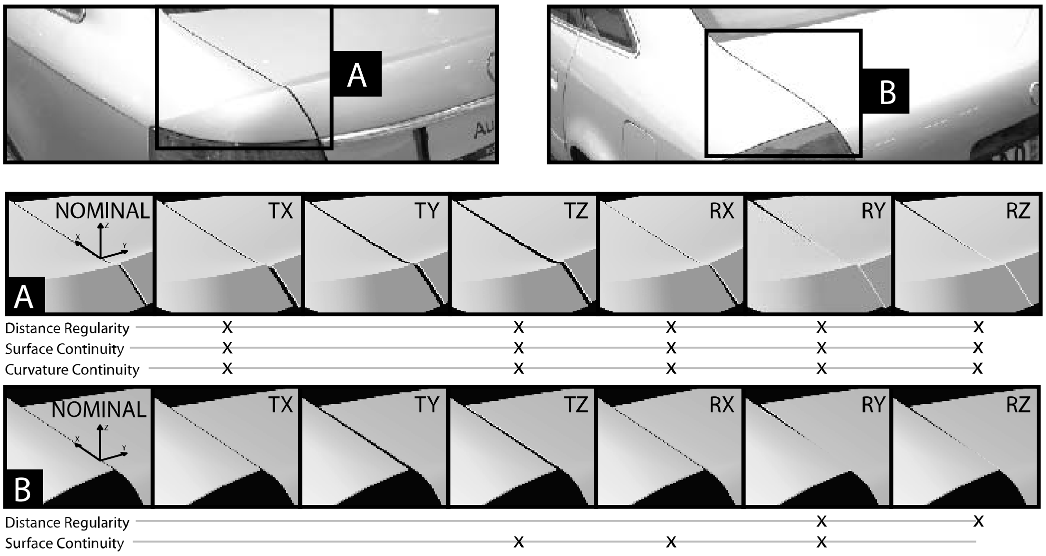

Figure 5. Visual constraints for split-lines

4. Perceiving a violated visual constraint

Parameters that can serve to amplify or suppress information on the nominal geometry once provided by the visual constraints can be identified using the model of communication described in 3.1 (Figure 6). A number of design parameters other than the amount and type of visual constraints will dictate the visual sensitivity. However, the parameters that vary during the rest of the communication process will determine whether these design parameters serve to increase or decrease the visual sensitivity.

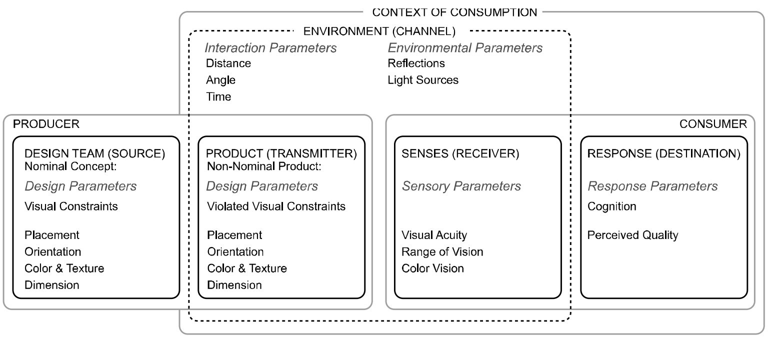

Figure 6. Identification of parameters influencing the visual sensitivity.

For instance, the consequences of the placement of a part affected by variation on the product can only be estimated if the areas of the product most commonly observed during user interaction are known. Figure 6 can serve as a checklist when taking different parameters into account in order to predict how a violated constraint will impact the VQA. The parameters listed in the boxes can serve to hide information on the violated constraints. Examples include whether the involved parts are placed underneath a product never interacted with from underneath, whether this area often is vaguely illuminated, if it is normally viewed at a long distance, or if the person is not likely to pay attention to the appearance of this specific part of the product. On the other hand, information on violated constraints could also be amplified to the extent that they most certainly will be detected. This could occur when the involved parts are placed in an area that will be in the range of vision for a long time during interaction and where the affected form elements are well illuminated and close to the viewer. In most cases, several parameters affect the probability of a geometrical deviation being perceived.

4.1 Visually robust solution

Despite the lack of knowledge regarding how different parameters amplify or suppress information on a violated visual constraint, the visual sensitivity of the tailgate of the Volvo SCC Concept Car (Figure 7) will be analysed using a number of assumptions on how visual constraints might be suppressed.

1. One interpart constraint is to expect symmetry in the relationship between the bottom of the tailgate and the sharp edge on the bumper. However, the distance between the two makes it difficult to perceive small deviations, compared to if the two curves had been in close spatial relationship to one another.
2. The overall shape of the tailgate is symmetrical, providing an intrapart constraint. It is, however, likely that the large scale makes it difficult to compare the two sides.
3. A whole product level constraint is that the relationships between the tailgate and the contours of the taillights are expected to be identical on both sides. Considering the relatively limited ability to view the two sides simultaneously, comparison between the two is difficult.
4. The distances between the contour of the transparent area on the tailgate and the taillights need to be equal on both sides. This is also hard to see because of the scale and the distance.
5. The most important visual constraint is the distance regularity between the tailgate and its adjacent parts. However, the colour of the tailgate is black. This makes the black split-line merge with the tailgate, making the distance difficult to distinguish.

Figure 7. Visually robust solution (reprinted with permission from Volvo Cars)

The solution contains a small number of visual constraints, especially since surface or curvature continuity between the tailgate and the adjacent parts are not required. This may well be a visually robust part solution for the vehicle, making it possible to allow for the small deviations that can occur without leading to functionality losses for the operation of the hatch without considerable VQA losses.

5. Consequences of physical and perceived deviations

The negative effects that arise when dimensions deviate from their nominal values have been described by loss functions [Taguchi, et al. 1989]. The quality losses associated with the VQA depend on the perceived deviation, as opposed to the physical deviation. A prerequisite for taking visual sensitivity into consideration is that the losses due to the perceived deviation are greater than those related to the physical deviation. For a specific dimension, this can be illustrated by a graph (Figure 8), where separate functions represent losses due to physical and communicative requirements, and visual sensitivity can be expressed in terms of the loss coefficient for the visual quality loss function, which does not need to be symmetrical. Defining visual quality loss functions for critical dimensions is one of the aims of evaluating visual sensitivity. One possible approach to visual sensitivity is to allocate especially sensitive features in areas where very small variation can affect functional requirements.

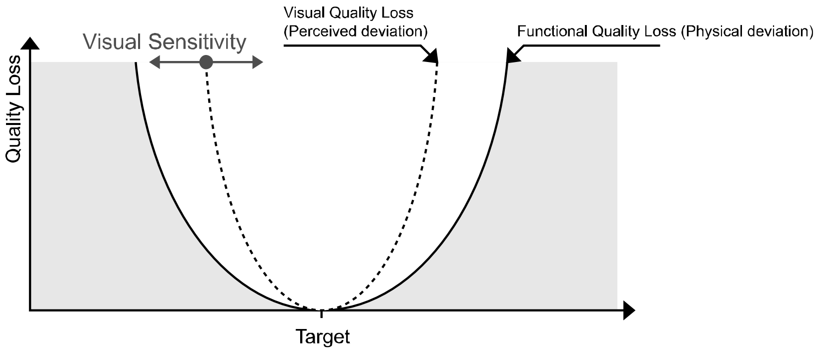

Figure 8. Loss function for perceived and physical deviations

6. Side-effects of visually robust product appearances

6.1 VQA improvements during industrial design through the consideration of visual sensitivity

Since a low visual sensitivity aims to increase the VQA of a product, it is important to mention that the overall design of a product will have an even greater influence on the VQA [Dagman 2005]. The design parameters influencing visual sensitivity will also generate the product appearance. Knowledge concerning how to increase the visual robustness of a product is to be used with great consideration of how the overall appearance of the product is affected. If considering visual sensitivity when creating an initial styling concept, particularly sensitive solutions could be avoided. If especially visually sensitive styling features are associated with a more appealing styling concept, it may in some cases still be worth spending resources to tighten tolerances in order to achieve a very small final product variation. Since all parameters that influence visual sensitivity are visible on an assembled product, they are determined by the exterior styling and should be considered by or in close cooperation with industrial design. If industrial designers create styling concepts with an awareness of the feasibility regarding dimensional variation, the risks of having to change the concepts further down the development process is smaller and lead times and costs could be decreased.

6.2 Impacts on semantic functions

Other critical consequences of visual robustness include the semantic functions directly connected to visually robust features. The division of a form has a significant impact on the product appearance even when the product is nominal. Visually underconstrained parts might, for instance, lead to the interpretation that the parts are supposed to move. Exposed split-lines can give the cue that something can be opened. Whether there is a value in developing products that look difficult to produce, thus signalling a high-quality production process, is also a relevant question.

7. Summary and conclusions

This paper has treated the concept of visual sensitivity, with the overall aim to provide a basis, in terms of a discussion and a framework, for gaining an understanding of how to avoid visually sensitive design concepts. The term visual sensitivity has been put in perspective to geometrical robustness and the visual quality in perspective to functional quality. In order to describe what makes assembled industrial products visually sensitive to geometrical variation, design has been studied as a process of communication, with the purpose of investigating how geometrical deviations are communicated to a customer. The concept of visual constraints has been introduced in order to describe how a product conveys information on its nominal geometry. Different categories of visual constraints are introduced, and primary focus is set on the interpart relationships. We have demonstrated that some visual constraints can allow for some form elements to move in one or many degrees of freedom. This makes the concept of visual constraints useful for explaining visual

sensitivity. Parameters that influence the visual sensitivity due to the context of consumption are also identified.
Finally, further work in the area of visual sensitivity to geometrical variation could comprise: a) a study of how information on the nominal geometry can be suppressed or amplified during the entire process of producer consumer communication, b) the creation of guidelines for how a product should be designed in order to optimise the visual robustness, and c) the investigation of the extent to which visually robust solutions impact the aesthetic value of a product by limiting the freedom of design.

References:

Crilly, N., Moultrie, J. and Clarkson, J., "Seeing Things: Consumer Response to the Visual Domain in Product Design", Design Studies, Vol. 25, 2004, pp. 547-577.

Dagman, A., "Increased Visual Quality through Robust Split-Line Design", ISSN 1652-9243, Department of Product and Production Development, Chalmers University of Technology, Gothenburg, 2005.

Maxfield, J., Dew, P. M., Zhao, J., Juster, N. P., Taylor, S., Fitchie, M., Ion, W. J. and Thompson, M., "Predicting Product Cosmetic Quality Using Virtual Environment", ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, Baltimore, Maryland, 2000, pp. 19.

Monö, R., "Design for Product Understanding", Liber, Stockholm, 1997.

Taguchi, G., Elsayed, E. A. and Hsiang, T., "Quality Engineering in Production Systems", McGraw-Hill Book Company, Singapore, 1989.

Warell, A., "Design Syntactics: A Functional Approach to Visual Product Form", ISBN 91-7291-101-8, Department of Product and Production Development, Chalmers University of Technology, Gothenburg, 2001.

Wickman, C., "Visualizing the Effect of Geometrical Variation in Assembled Products - Predicting Visual Quality Appearance", ISBN 91-7291-553-6, Department of Product and Production Development, Chalmers University of Technology, Gothenburg, 2005.

Karin Forslund, M.Sc.
Chalmers University of Technology
Department of Product and Production Development
SE-412 96 Göteborg, Sweden
Tel.: +46 31 772 8285
Fax.: +46 31 772 1375
Email: karin.forslund@me.chalmers.se
URL: http://www.ppd.chalmers.se