Requirements for highly interactive system interfaces to support conceptual design

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Abstract: During the last two decades, many breakthroughs occurred in the development of CAD systems. However, some design activities are not yet successfully supported by CAD systems. This is especially true for the conceptual phase of industrial design. In this part of the process, synthesis and creativity play an important role. Computer-aided Conceptual Design (CACD) systems are supposed to provide natural forms of expressing design intent. The creative power of the designer must not be hindered by difficult interaction procedures. Therefore, the designer's natural way of communication must be the starting point for the interaction. Highly interactive system interfaces have to fulfil new requirements. A survey of requirements was composed from literature. In addition, a series of conceptualisation cases provided empirical data on interaction problems during conceptual design. The identified problems could be related to a number of requirements from the literature. Furthermore, additional requirements could be derived from the cases. The total set of requirements will be evaluated on several levels of abstraction, and implemented in a support system for the conceptual design of shape.
Keywords: Conceptual design, Natural communication, Interactive environments, Computer-aided shape conceptualisation, Voice- and gesture-based input.

1. INTRODUCTION

In the conceptual phase of the design process, the main design requirements are known, and a global concept of the product emerges as a whole. Synthesis and creativity play an important role during this phase. Computers are powerful in many calculations and representations of the well-defined models during detail design. However, how can they handle the fuzzy and incomplete descriptions, which occur in the conceptual design? For effective interaction during conceptual design, emerging ideas must be expressed in such a way that a system can interpret them. Interface systems should adapt to the user's natural way of expressing and describing, at one hand, and transform it into data that can be understood by computer systems, at the other hand.
We distinguish different sets of requirements for this high-level human-computer interaction. At first, there are the so-called external requirements, which reflect the

expectations of the user against the CACD systems. They will have implications for the specific functions and data structures of the CACD system, together with the internal requirements. The generation and evaluation of the internal requirements are described by Opiyo et al. [1998]. This paper addresses the external requirements and their effects.
Several researchers listed requirements, from different points of view, either for CAD systems in general, or more specifically, for CACD systems. Section 2 summarises their findings.
Empirical research can give a closer view on interaction problems during conceptual design. Section 3 discusses which problems were observed during a conceptualisation experiment. Finally, section 4 relates the observed problems to the listed requirements and proposes some additional requirements for highly interactive interface systems.

2. REQUIREMENTS FROM LITERATURE FOR CAD SYSTEMS

Blessing [1994] inventoried requirements for process based design support systems. This inventory contains many issues that are relevant for the conceptual phase of the design process. Specific requirements for conceptual design are also mentioned by e.g. van Dijk [1994], Kolli & Hennessey [1993] and Tovey [1992]. We categorise the requirements for conceptualisation as follows:

(1) the need to support the creative activity of designers,
(2) natural interaction methods,
(3) the use of examples and real objects,
(4) rapid feedback and evaluation,
(5) knowledge about the process and the artefact, and
(6) information storage and retrieval.

The requirements from literature are ordered to the above categories, and listed in the following subsections.

2.1 Support the creative activity of the designer

1. Creativity should be supported, not hindered.
2. A support system should be subordinate to the user.
3. Different approaches should be allowed, e.g. the designer should be free in the sequence of activities, in the number of generated alternatives and in the use of selection criteria, arguments and decisions.
4. The interaction method should be adapted to the user's approach.
5. Ideation should be stimulated by an exposition of sketches.
6. Automatic generation of alternative concepts should support the ideation. Systems for this exist in specific domains, e.g. Horváth & Wieser [1988] and Myint & Tabucanon [1998]. For industrial design, however, generation of alternative concepts should be possible for a variety of domains, and starting from vague concept descriptions.

2.2 Natural interaction methods

7. The interaction should be natural to the designer.
8. The interaction should be consistent with the designer's way of thinking. An implication is that an interactive design environment should build an image of the designer's way of thinking.
9. To make interaction feel natural, designers must be able to benefit from the skills they have, i.e. it should be possible to use both hands simultaneously, sketching should be supported, etc.
10. It should be possible to simulate mechanical tools and methods, e.g. bending, bowing, twisting or tapering.
11. Interaction with virtual objects should be experienced like interaction with real objects.
12. The use of multiple modalities should be supported.
13. Symbolic input must be avoided and the user must not get lost in multiple layers of menus.
14. It should be possible to optimise the dimensions and locations of shape, e.g. by the use of edges, borders and other types of constraints.
15. It must be possible to provide non-precise input without making it explicit.
16. Interaction tools or methods should not give the user the feeling of being outside the real world. Rosenblum et al. [1998] mention this as a main drawback of traditional Head Mounted Devices.

2.3 The use of precedent concepts and real objects

17. The use of precedent concepts should be allowed.
18. It should be possible to use predefined shape elements.
19. It should be possible to use non-native virtual models.
20. It should be possible to use physical products.
21. It should be possible to use real objects in combination with gestures and oral comments. Logan & Radcliffe [1998] captured the power of these combinations for different functions.
22. There should be freedom to experiment with shape. Digital examples should be easy to modify, e.g. by direct manipulation or by voice commands.

2.4 Rapid feedback and evaluation

23. If an idea emerges, its consequences should become clear as soon as possible. Sketching plays an important role in this clarification.
24. Reviewing alternatives must be readily possible.
25. It should be possible to modify previous input and this should be supported by suggesting possibly affected product elements and relationships.
26. Perception and action should be coupled in a natural way [Djajadiningrat, 1998].
27. Interaction methods should not be hindered by poor resolution and time lags. Proper hand-eye co-ordination requires a clear and precise image of the hand [Poston & Serra, 1994]. If a user manipulates a digital object, the displayed image of the object should react within narrow time limits [Groen & Werkhoven, 1998]. Too long time

lags cause dramatic decreases in user performance. Feedback from action to perception takes 200-500 msec. Rapid actions therefore have to take place in automated sequences of motor acts [Wearn, 1989]. Superfluous action-perception loops must be avoided. For these reasons, interaction methods should exploit the user's natural and learned skills.

2.5 Knowledge about the ongoing design

28. Context-sensitive assistance should be provided, i.e. suggesting relevant knowledge, methods, tools and data from previous design projects.
29. Context-sensitive guidance should be provided, i.e. to achieve a balanced approach, or to find the next step in solving a problem, etc. [Blessing, 1994; Chin, 1998].
30. Tracking the complete conversation is important to be able to understand what the designer is doing at a given moment [Burger & Marshall, 1998]. For example, pointing gestures must be interpreted in a highly context sensitive way [Wahlster, 1998].
31. Highly interactive systems must be aware of the user's and their own intentions, e.g. to be able to clarify misunderstood explanations [Moore & Paris, 1998].

2.6 Domain Knowledge

32. It should be possible to provide the designer with relevant knowledge, e.g. theories and formula's, rules and guidelines, checklists and catalogues; existing product states and their relationships, e.g. working principles and concepts.
33. The designer must be able to backtrack data of his concepts, such as:
    proposals and alternatives,
    arguments and decisions for or against proposals,
    personal notes.
34. The system should facilitate rapid capturing of ideas as they occur [Kolli & Hennessey, 1993; Tovey 1992].
35. The system must be able to fill in data that the designer does not yet want to worry about.
36. It should be easy for the designer to re-use data of previous projects.
37. The system should enable easy retrieval of process and product data stored in the system.
38. The system should provide a structure to document all project data (i.e. process and product data) generated throughout the process.

3. INTERACTION PROBLEMS DURING CONCEPTUAL DESIGN

3.1 The conceptualisation case

Empirical data on the designer's interaction was captured during a series of conceptualisation experiments. The design assignment concerned a bicycle lighting system. The conceptualisation case was performed 13 times, each time by another subject. Subjects were near graduate students of our faculty of Industrial Design Engineering. The subjects got 2.5 hours to generate a concept and to make a description to demonstrate that the concept would be able to satisfy the requirements of the design assignment. The concepts were rated to the (weighted) percentage of satisfied requirements. The generated concepts and the protocol files of the first 10 cases can be found in van Breemen [1996]. The protocol data were analysed and problems during the conceptualisation cases were identified. A summary of the identified types of problems is given, in section 3.2. Next, an activity from the conceptualisation process is taken as an example, in section 3.3. It will be discussed how the individual subjects performed this activity and what problems they encountered.

3.2 Identified problems

Based on the empirical data, we identified the following types of problems that hindered the progress of the conceptual design:

1. Performing an activity that has no contribution to the generated concept (the same activity was repeated, the subject deviated from the assignment, or irrelevant information was applied).
2. Sticking to a sub-problem without progress.
3. Going into detail before having a global understanding.
4. Unclear information requests.
5. Insufficient calculations.
6. Evaluation was not sufficient, or too late.
7. Documentation was insufficient.
8. Some requirements were not addressed
9. Decisions were postponed or revisited.
10. Relevant information was retrieved, but the subject was not able to apply it properly.
11. Sub-problems were not understood.
12. Errors occurred in solutions.
13. Some information was not available.

The elaboration will be restricted to the problems that occurred during one specific type of activity.

One activity that all subjects had to perform, was the consideration of the electric generator's efficiency. This activity will be discussed in the next section.

3.3 The consideration of the generator efficiency

The subjects had to conceptualise a bicycle lighting system. This system should be able to power the bulbs also at low speeds, or when the bicycle is standing still for a short time. For this reason, the system must contain a generator, batteries and an electronic circuit. Requirements were put on the product's image, its efficiency, the ease of mounting it onto a bicycle, etc. The efficiency of the generator played a central role in the conceptualisation.

Subject number	Efficiency derived from/by: Calculations	Example	Reasoning	Rating [1]
3		•		75
13		•		67
10	•			67
2	•			58
9	•	•		56
4			•	56
7	•	•		46
8			•	44
11	• [2]			36
12	• [3]			31
6			•	29
1			•	29
5			•	13

[1] - Percentage of satisfied requirements (weighted value).
[2] - Calculation attempt, but not successful.
[3] - Calculation, however with wrong assumption for revolution speed.

***Table I**; Generated data about the output power of the concept.*

The efficiency depends on many parameters, and some of these parameters also influence other characteristics of the generator, e.g. its external dimensions, its output voltage and the way it must be driven. The subjects had to consider the individual parameters in order to synthesise a balanced concept. Some subjects used an existing generator as an example and modified only a few parameters. Some subjects first generated an image of the generator geometry and then verified its efficiency by reasoning. Other subjects studied the applicable calculation models and chose values for each individual parameter, until they achieved a satisfactory calculation result. Two subjects derived their concepts from an existing generator *and* evaluated the efficiency by performing the applicable calculations. Apparently, at least four different approaches were applied. Table I depicts the methods that were used by the individual subjects. The table also reports the ratings of their concepts, expressed in the percentage of satisfied requirements. From this table, it appears that five subjects motivated the efficiency of the generator by reasoning. Generally, their reasoning was not very convincing. One subject (subject 4) did not understand that the cyclist had to deliver the extra power necessary to light the bulbs (problem 11, see section 3.2). None of the above five subjects evaluated the generator efficiency in a proper way (problem 6). They did not even present the data necessary for such an evaluation (problem 7). These subjects hardly addressed the requirement on the efficiency (problem 8).

Examples of existing generators were used by four subjects. They modified only those parts that didn't influence the elicited voltage, e.g. the housing, the driving method and the battery supply. The electrical and magnetic elements were not changed. In addition, the revolution speed was kept the same. In this way, the subjects avoided the risk of miscalculation, and yet they could be sure of a working product. One subject (subject 13) convincingly claimed that the output power, delivered by his concept, was sufficient. His concept was based on an existing generator with known, sufficient values of power and efficiency. The rating of his concept was relatively high. Apparently, using an example as a starting point *can* be a successful approach.

Only six out of 13 subjects actually calculated the output power of the generator. One subject (subject 6) asked repeatedly if it was really necessary to calculate the produced voltage. Finally he requested the necessary equations, but he did not apply them. This observation is consistent with the statement in section 2.2, that symbolic input should be avoided.

Subject 11 attempted to calculate the generator power, but he did not succeed. He was not able to apply the revolution speed of the generator rotor (problem 10). Subject 12 used a wrong value for the revolution speed, because he mixed up meters per second with kilometres per hour (problem 12).

4 THE RELATION WITH REQUIREMENTS FROM LITERATURE

The problems described in the previous section relate to a number of requirements for CAD systems mentioned in section 2. Individual subjects used different approaches. Possible support for the subjects depends strongly on their approach, so requirements 3 and 4 are applicable. We observed the use of examples, including physical objects, textual descriptions, graphical representations and oral explanations. Requirements 12, 17, 20, 21 and 22 apply to this. Requirement 23 is applicable to the lack of evaluation of many subjects. Requirement 13 is applicable to the observed reluctance to perform calculations. Furthermore, many subjects found it difficult to find appropriate values for all the involved parameters. Often this was a process of trial and error, on which requirements 25 and 35 were applicable. The subjects requested the desired data from an expert. The expert generally understood a subject quickly, because he knew what the subject had done so far, he could see the subject's sketches and he generally was aware of the subject's goals. Therefor, requirements 28-31 played an important role, and many requirements from section 2.6.

Problems observed during conceptualisation case	CAD requirements from literature	Additional requirements
1. Activity without contribution	29, 33, 38	f, h
2. Sticking to a sub-problem	28, 29	f, g
3. Detailing before having a global understanding	15, 23, 35	f, g, k
4. Unclear information requests	8, 30, 31	
5. Insufficient calculations	7, 13, 22, 35, 36	
6. Evaluation was not sufficient, or too late.	23	a, b, g
7. Documentation was insufficient.	24	g
8. Some requirements were not addressed	29, 32	g
9. Decisions were postponed or revisited.	29	f
10. Unable to apply information properly	28	j
11. Sub-problems were not understood	31	j
12. Errors occurred in solutions	31	i, j
13. Some information was not available.	32	c, d, e

Table II*; Comparison of observed problems and requirements for CACD.*

Table II gives an overview of the observed problems and requirements for CACD systems. The table contains two columns of applicable requirements for CACD systems. One column shows requirements derived from literature. The other column shows an additional set of requirements. The requirements of this set could be derived from the observed cases, and were not found in the referred literature in these specific terms. The set contains the following requirements:

a. The design requirements must be clear.
b. The design requirements must be translated into ready-to-use criteria for evaluation.
c. It should be possible to retrieve additional information about the design requirements.
d. It should be possible to retrieve additional information about the user group.
e. It should be possible to retrieve additional information about the product type.
f. Approaches must be applied with which the designer makes rapid progress.
Progress is made by:
satisfying a requirement,
or by fulfilling a condition for satisfying a requirement, e.g.
clarifying a problem, gathering the necessary information or
solving a sub-problem.
g. Information must be available about the status of the design concept and the progress of the design process.
Information must be maintained about:
which design requirements are addressed and which are not;
which design requirements are satisfied and which are not;
which design requirements are not explicitly mentioned, but must yet be satisfied;
which information is already available and which must yet be retrieved.
h. It must be clear which information is relevant.

i. The necessary information must be easy accessible.
Users must be able to find specific data by browsing through the available data, rather than formulating a detailed and exact query.
j. The necessary information must be quickly understandable.
k. Parts of the concept must not be elaborated too detailed before any confidence exists about the global concept.

This set of requirements will be combined with those of section 2, evaluated on several levels of abstraction [Opiyo et al., 1998], and implemented in a support system for the conceptual design of shape.

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