1

Capturing and Deploying Design Decisions

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Abstract

This working paper describes an evolving design rationale model intended to capture the design process of a physical artefact. The model is intended to be useful for supporting design and redesign, for enhancing communication amongst designers and design teams, and for various later life-cycle activities such as creating and maintaining product configuration models for configuration design, or analysing the designed artefact during production engineering. Moreover, the model should be useful for assessing the completeness, validity, and consistency of the design process itself for design process improvement activities.

The model essentially views design as a web of interdependent decisions chosen from a collection of alternative designs according to some criteria. The paper describes the basic ideas of the model, and demonstrates its feasibility with a "lo-fi prototype". Issues and topics of future work are also discussed.

Keywords

Product design, product development, design decisions, design rationale, design history, design process modelling, product modelling

1 INTRODUCTION

Product design is knowledge intensive. Several studies indicate that designers spend more than 50% of their time to identify and collect various types of information relevant for a design project, and only a lesser part for direct design activities.

Potentially relevant information for product design comes from many sources and includes many types of data, such as customer's requirements on the functionality and usability of the product, competitive information from markets, design data on old or competing products, available production technologies and materials, internal and external standards, legal constraints, and so on. The quite formidable task of the designer is to recognise the need of information necessary for executing the design task, and collect the relevant information in valid and useful form. He or she must also balance the effort spent for these activities against the constraints posed by the schedule and budget of the total design project.

Indeed, it is no surprise that design errors or suboptimal designs emerge. Unfortunately, often these are only recognised at a late stage of the design process, leading to high cost and blown schedules.

We hypothesise that nearly all design problems can be traced back to problems of the basic information used to characterise and constrain the design task. In fact, three categories of data deficiencies seem to dominate as underlying reasons for design errors:

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1. The relevance of some type of data is not recognised at all. For instance, a Finnish designer of an elevator car door does not recognise the relevance of a Malaysian fire safety standard for his design.
2. The relevance of data is recognised, but validity of available data is not assessed, resulting in the use of invalid or incomplete information. For instance, incomplete data of user characteristics leads to a design for an electronic pulse measurement device that joggers cannot learn to use.
3. The relevance of data is recognised and valid data is collected, but the designer simply forgets to deploy the information during design. For instance, even though design specifications state that product safety must be on high level, the designer forgets this requirement and designs a product with small loose parts, which may be dangerous for small children.

In summary, we state that in case 1, the design process is *incomplete*; in case 2, it is *invalid*; in case 3, it is *inconsistent*. An incomplete design process fails to take account important information, an invalid process uses false information, while an inconsistent design process fails to deploy information during design activities.

Incompleteness, invalidity, and inconsistency become particularly acute during the redesign or later life-cycle activities of a product. In a typical redesign scenario, the designer allocated to the redesign task is not the same person, who originated the product. Personal communication is not possible or feasible, so he or she must rely on formal and informal product documentation, such as CAD data, textual documents, prototypes, specifications, data sheets, BOM data, and so on. Unfortunately, nearly invariably these types of product data fail to indicate completely the relevant information, which constrained the original design, leading to incompleteness. Some of the original design information may have lost its justification, leading to invalid design. Finally, the new designer may fail to take into account some of the data, leading to inconsistent design. Similar comments can be made on other life-cycle activities, such as production engineering, where people other than the original designer must interpret the design.

Present state of the art of product modelling is mainly aimed at documenting the outcome of a design process. The tools and techniques cover (more or less) product geometry, its dimensions and tolerances, geometric features, assembly relationships, kinematic and dynamic data on mechanisms, and some types of functional information. Research of conceptual product structures and patterns is also emerging. However, far less work has been spent on recording the "deep" data dependencies between the various types of product information resulting from a design process and the various types of basic design information used in their design.

The long term aim of the research reported in this working paper is to develop a design process model, which addresses directly the deficiencies discussed above. In particular, the model should be useful for supporting design and redesign, for enhancing communication amongst designers and design teams, and for various later life-cycle activities such as creating and maintaining product configuration models for configuration design or for analysing the artefact during production engineering. Moreover, the model should be useful for assessing the completeness, validity, and consistency of the design process itself for process improvement activities.

The paper reflects the (relatively immature) stage of our evolving work. In section 2, we discuss some past work, which has influenced our own. Section 3 concentrates on one important aspect of any design process model: the representation of design evolution. On the basis of this discussion, section 4 synthesises a "straw man" design process model. The following three sections give a small case study illustrating the use of our model to characterise design evolution through a design-redesign cycle. Finally, sections 8 and 9 give our conclusions and draft research agenda for the future.

2 RELATED WORK

According to (Mostow 1985) a comprehensive model of design should support the representation of the following types of information:

1. The state of design in form of descriptions of the design object.
2. The goal structure of the design process, in which goals are prescriptions of how the descriptions of the artefact should be manipulated.
3. Design decisions, which are choices between alternative designs.

4. Rationale for design decisions to show the justifications for goal selection.
5. Control of the design process guides the selection of the best goal to work on and the best plan with which to achieve it.
6. Learning in design both of general knowledge about the domain and of specific knowledge about the problem.

Representation of such data on design processes is an important research topic of long standing within the realm of "Intelligent CAD". Refer the IFIP publication series on Intelligent CAD and Knowledge-Intensive CAD for an comprehensive trace of past research. Instead of trying to give a complete literature study, we will in this section mention only those works which directly have influenced the present work.

In an early work, one of us constructed a system intended to capture the evolution of an artefact through conceptual and detail design and redesign (Mäntylä 1990, 1991). The system provided rudimentary support for versions, alternatives, and inherited constraints roughly modelling the level of commitment of a designer to a particular design item.

The issue-based information system (IBIS) methodology (Kunz 1970) aims to capture a design process as it happens. It defines a set of entities: issues, positions, and arguments. Discussion starts with an issue, which is the unsolved problem or question. Positions are solution alternatives to the issue. Arguments either support or object the positions (Conklin 1991). IBIS helps to form the structure of questions and answers produced in design process.

Several variants of the IBIS methodology have been investigated. For instance, indented text IBIS (itIBIS) is a notation by which it is easy to record the process. It uses indentation to represent the hierarchical relationships among the nodes (Conklin 1991). In testing itIBIS in a project, it emerged that captured information was useful when personnel changed and that the meetings became more productive. However, in the later phases of the project the amount of information was large and the required information was hard to find. Graphical IBIS (gIBIS) is a hypertext software tool for building IBIS networks (Conklin 1988). The use of gIBIS was found to be most rewarding for a project that had specific goals, an extended time frame, and a clear process that was used by all project members.

Taylor and Henderson (1993) give an example of an integrated product model created using a "metamodel" structure on top of ACIS. The model combines functional information, structure information, and geometric features. It can reason about the things included in the model and answer questions on them. The paper gives and interesting case study illustrating the characteristics and limits of the approach.

Shah et al. (1996) describe a framework for constructing what the authors call a *Design History System* (DHS). The explicit aim is to record not only the various versions of an evolving design, but also the reasons for the versions and configurations and the temporal characteristics of the design process itself. The resulting model contains four kinds of information elements, namely product data, design steps, relationship between product data and design steps, and rationale. Design steps are modelled using a taxonomy of step types such as "obtain information", "refine", "generate", and "check". The rationale is characterised in terms of the issue considered, various alternative designs, arguments for or against the alternatives, and the final outcome of the decision. The resulting system is implemented as a combination of a WWW-based user interface and an object-oriented model database server.

Peña-Mora et al. (1995) give an extensive bibliography of models and systems, that capture design rationale, and classify them according to the number of designers supported, the use of computer support in recording and using the design rationale for conflict mitigation, and the support provided by the computer during conflict mitigation. According to the classification, most of the research in design rationale has focused on capturing design rationale without concern for its later use. Thus, research for capturing and recognising the information, which is needed to support later stages of design and to assess the design process, is necessary.

3 SOURCES OF DESIGN EVOLUTION

Tracing the evolution of a product through design and redesign is a central requirement for any reasonable design process model. At the present stage of our work, we have chosen to emphasise this aspect.

Pressure for product evolution comes from three sources: *product, technology* or *process.*

Product driven evolution originates from the event that the designed product does not meet the requirements set to it, and it has to be changed. Necessary changes may relate to functionality of the product, or the actual entities making up the product. For example, a pump might need to provide more fluid pressure than the current product is capable of, or the assembly of the pump is so difficult that the number of components has to be reduced.

Technology driven evolution means that somewhere somebody has made an innovation that can be applied to improve radically an existing design. The innovation may originate in a completely different product, but turns out to be useful for the product. Well known examples include the use of solar cells (originally developed for special military applications) to power consumer products such as calculators.

Process driven evolution considers more the design process itself than the product. The deployment of a new design method or design assessment method is one type of such evolution. Examples include the use of rapid prototyping or simulation. Another type of process innovation leading to product evolution is a new organisational structure for design such as the deployment of integrated design teams for concurrent engineering.

These different sources of evolution put requirements on the model of the design process. Product driven evolution is triggered by new product requirements that arise during the design process or from a later stage of product life cycle, or by a product assessment that notices the failure of a product in some critical aspect. To improve the product, incremental redesign is required. To be effective, such redesign should eliminate the original reason for the failure, instead of just patching up its symptoms. Therefore, a design process model should make it possible to trace back through a design process to find the design data elements that contribute to the design object properties relevant to the assessment.

Technology driven evolution is triggered by realising that an innovation is applicable to the present design. This commonly results in a radical redesign of the product, taking advantage of the salient new characteristics made possible by the innovation. Let us imagine, for instance, that reliable voice recognition becomes available. If applied to the design of computers, a radical new design that eliminates the keyboard might emerge, resulting in wrist computers and like.

Process driven evolution is triggered from realising that the present design process is not satisfactory in some respect. A design process model should ideally support the analysis of design processes that forms the basis of the needed process assessment. For instance, the innovation of a design process might be measured by the number of design alternatives which were considered during the course of the design. If the number is low, we may conclude that a process improvement that makes it possible to generate and study more design alternatives is necessary. Moreover, the number of alternatives compared to the time used is quite a good measure to assess the efficiency of a product design process. If we can develop more alternatives in the same time, the process has improved. Another type of process evolution is improvement of design assessment methods. If many design errors emerge late in a design, design assessment improvement for the earlier stages is clearly needed.

We may conclude that a design process model should possess the following characteristics (amongst others we choose to ignore at the present):

- the model evolves with design process and product evolution
- the model gives the data needed to assess the completeness, validity, and consistency of a design process
- the model delivers information for all who need it
- the model captures design alternatives, the criteria by which they are judged, and the methods by which the criteria are assessed
- the model shows the design decisions and the rationale for them (what alternative is chosen and why).

One further essential requirement to the model is that it should be easy to use: if generation of a design history interferes with the actual design work, designers are not likely to do it. The usefulness of the model should be clear already from the beginning of design, so that designers want to use it during the whole process to help them manage the large amount of information related to their work.

4 MODEL STRUCTURE AND CONCEPTS

In this section we synthesise a "straw man" design process model that can cover (many of) the desired characteristics discussed in the previous section. Here the meaning of the used concepts are clarified and the structure of the model is described; the following sections give further clarification by means of a case study. Figure 1 represents the main concepts and their relations.

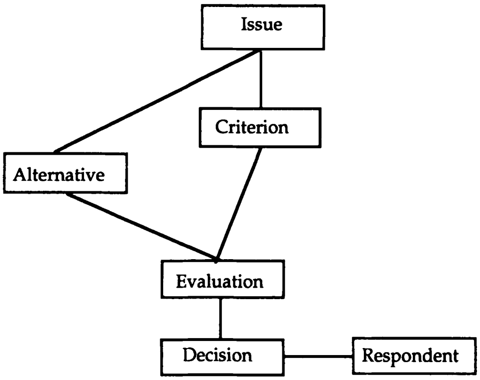


Figure 1 Concepts of the model.

Issue is a design task or problem which is supposed to be solved. Depending on the progress of a design process, issue can be an abstract need of a new product or fairly detailed design problem related to the physical structure of the product. During the design process issues become more detailed and concrete. Issues form a hierarchy through the decision on an issue spawning new subissues.

Alternative is a possible design solution for an issue. Like issues, they range from abstract to detailed depending on where one stands in a design process.

Criterion sets goals and restrictions to issues. Criteria describe the requirements which the product has to fulfil. For example, in the issue of restricting the people from entering a room housing classified information, the criterion might state that we do not want to use any separate things such as keys or cards. This restricts the possible alternatives. There are different types in criteria. One type of criterion may be fulfilled totally by an alternative. Another type has to be checked repeatedly during the design.

In *evaluation* a criterion related to issue is compared to the attributes of the alternative. Different kind of evaluation methods can be used for a criteria. For example, there are various methods for assessing the cost for product.

In *decision* alternatives are evaluated so that the most suitable alternative can be chosen. The results of evaluation, together with the method to choose the alternative, then indicate the reasons for the decision.

Respondent is a person or a group that makes the decision and is responsible for making decisions or realising the solution of issue.

Design context describes the evolution of the design process. It includes a trace of the earlier decisions, including the past issues considered, alternatives studied, criteria used to judge the alternatives, and evaluations of the criteria. A product model reflecting the decisions is also included, as well as the current issue and criteria being considered. See figure 2 for illustration. Design context sets the focus of design to the current issue.

The different model elements can be thought of as base classes of an object-oriented representation. For instance, we expect to see the usefulness of an issue taxonomy, classifying the issues to different kinds such as functional, safety, environment, cost, marketing, etc. Such a taxonomy might form a basis for assessing the completeness of a design: if cost issues do not appear in a design model, it is quite likely that the process is incomplete by failing to take product cost into account. Similarly, criteria and evaluations might be classified and analysed to discover the consistency of a product design: if environment-friendliness is an important issue for design, but no assessments of environmental performance are performed, the process is likely to be inconsistent.

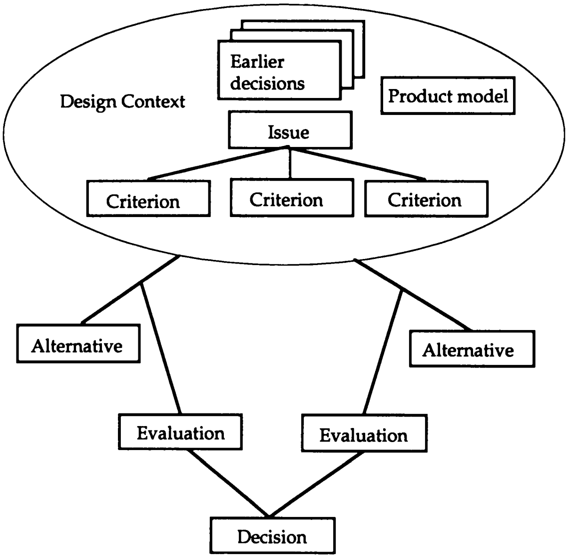


Figure 2 Example of the structure of the model.

5 CASE STUDY

To illustrate the concepts of the model further, we have gathered the design decisions and related descriptions behind the design of a robotic planar positioning device, which is suitable for various manufacturing, laboratory measurement and instrumentation tasks. Figure 3 shows the detailed structure of the first generation of the device.

The design in question was designed and manufactured at the Thomas J. Watson Research Center of IBM (Hollis 1985, Musits 1987). With this example we try to validate our model and show that it can be able to fulfil the requirements related to design as described in section 3.

The case study is partially written in the form of a design narrative which may not in all aspects correspond with the real truth of the design process, which is not directly accessible to us. Yet we hope to expose some of the real issues of a design process.

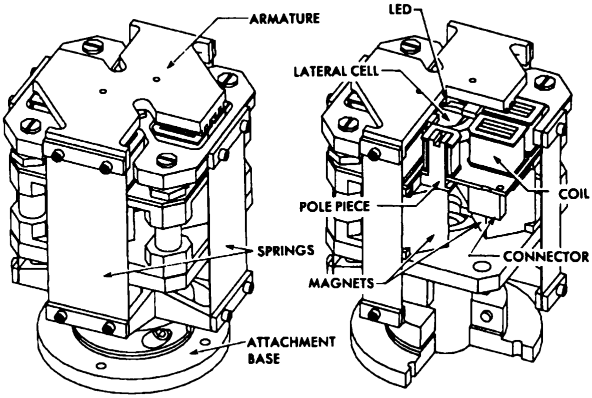


Figure 3 The fine precision positioner.

6 THE FIRST DESIGN ROUND

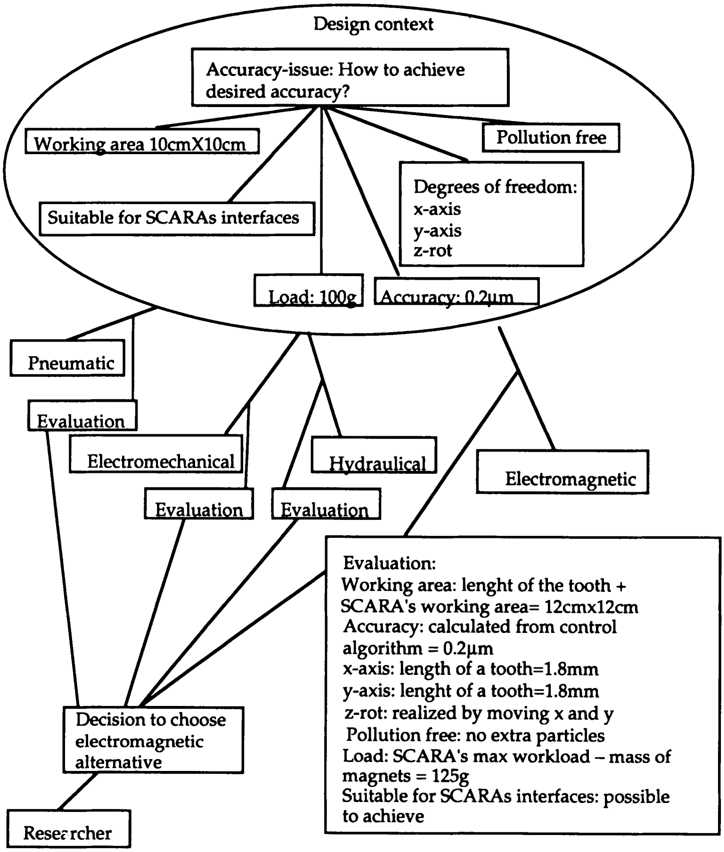
The first need for the product came from an internal customer. In a department of IBM Research, a very accurate robotic positioner was needed to perform laboratory measurements of individual semiconductor devices within an integrated circuit.

The intended use sets a number of criteria to the design. To access individual gates and wires, the desired positioning accuracy was 0.2 μm. Another important requirement was pollution-free operation, which means that no particles or oil leakage are allowed while performing the measurements. The measurement probes are not heavy, so it is enough that the positioner is able to carry load of 100 g. For reaching the full area of a circuit, the positioner should be capable to move along x-axis and y-axis, and preferably rotate around z-axis. To cover the full area of a silicon wafer, a total working area of 10 cm x 10 cm was required. As IBM SCARA robots were available in plenty, a suitable interface with a SCARA arm was needed.

Figure 4 gives the resulting initial model of the design process. As this is the initial model, no trace of earlier decisions is present. First issue considered is related to accuracy: How to achieve the desired accuracy? There are many commonly used techniques to move a robot's hand: pneumatic, hydraulic, and electromechanical. Unfortunately, these fail to satisfy the criteria for pollution-free operation: in pneumatic solution the leaking air can be dusty, in hydraulic solution there may be oil leakages, and in electromechanical solution metal particles can disturb the operation.

In addition to the conventional ones, the researcher in charge of the design also got a novel idea of using an electromagnetic actuator. As shown in the schematic of figure 5, this allows accurate control of the position of an armature with respect to the body of the device by means of a control current flowing through a coil wound around pole pieces formed in a permanent magnet and shaped as "teeth" matching another set of teeth in the armature. Figure 4 shows the evaluation of the electromagnetic alternative. It satisfies the criteria, and the researcher decided to use that technique.

The chosen alternative defines some structural entities such as the magnet and its poles and principle of the controlling the movement by current in coils around the poles. The next issue is: What is the spatial structure of the device? Its criteria are that it must be manufactured at IBM Research workshop, and that the gap between armature and body teeth should be kept constant while providing the required degrees of freedom of motion.



Evaluation:
Working area: lenght of the tooth + SCARA's working area= 12cmx12cm
Accuracy: calculated from control algorithm = 0.2µm
x-axis: length of a tooth=1.8mm
y-axis: lenght of a tooth=1.8mm
z-rot: realized by moving x and y
Pollution free: no extra particles
Load: SCARA's max workload – mass of magnets = 125g
Suitable for SCARAs interfaces: possible to achieve

Figure 4 Start of the first design round.

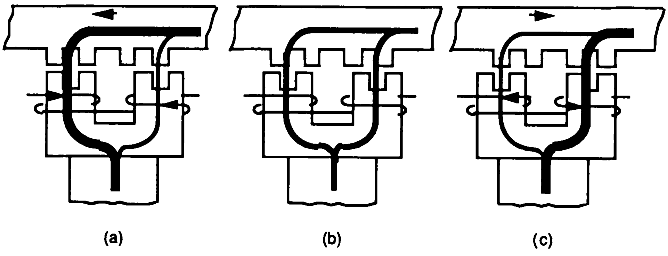


Figure 5 Physical principle: electromagnetic actuator (Mäntylä 1990).

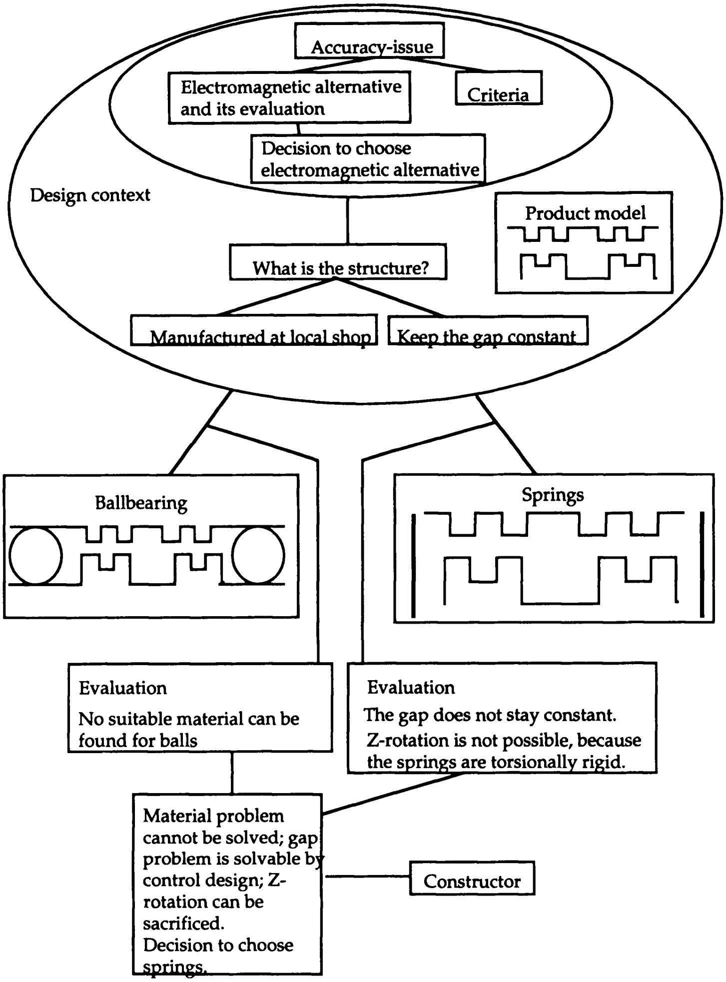


Figure 6 Next step in the first design round.

Figure 6 shows the model for this issue. Observe that the design context now contains a trace of the earlier design decisions (in this case, just one decision) and a product model specifying the essential elements of the solution principle chosen in the decision.

From the design context the constructor can get all things that influence the possible alternatives. In this case, he found two alternate solutions. In first, antimagnetic balls are located in between the components. In the other, steel springs are used to maintain the gap and still allow the movement. In evaluation, neither approach is perfect, but the spring solution is found to be feasible after evaluating the different criteria: while z-rotation is not possible, this criterion is not essential, and while the gap between armature and body does not stay constant, this problem can be compensated in control system design. Therefore, the constructor decides to choose springs.

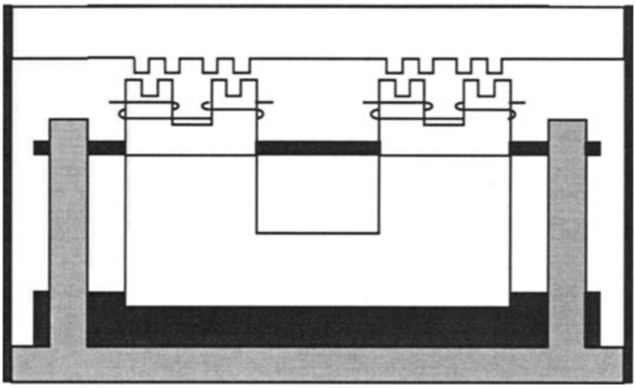


Figure 7 Resulting design in the first design round.

After deciding to use springs many detail design decisions about the structure, components, and various dimensions and tolerances have to be made. The result of these tasks is shown schematically in figure 7. The final result of detail design as a 3-dimensional model is shown in figure 3.

7 THE SECOND DESIGN ROUND

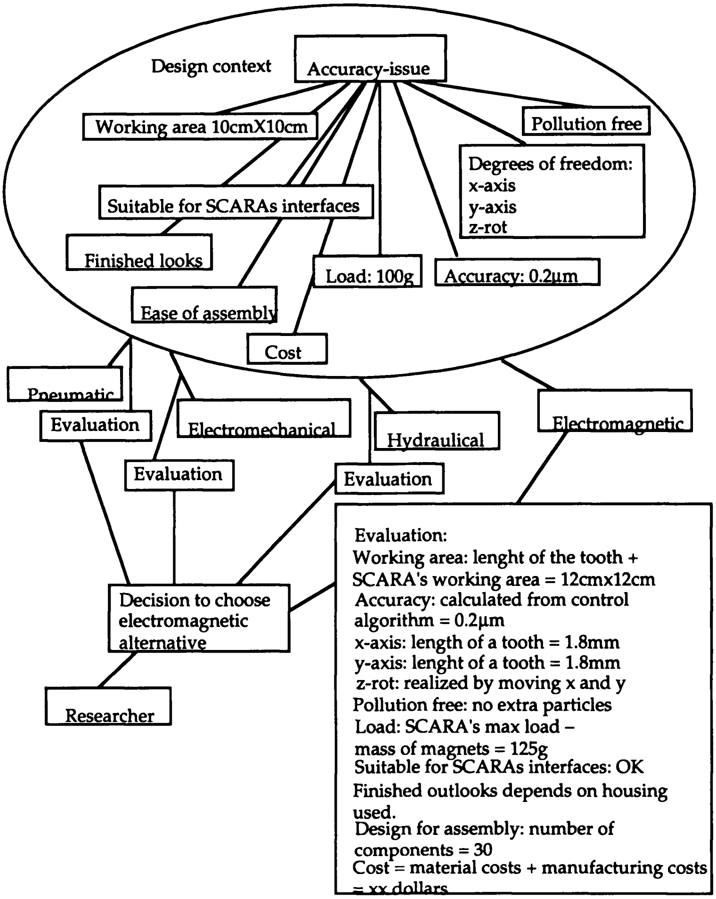
7.1 Product Driven Evolution

The initial design was built and tested. However, the product turned out to be quite expensive and difficult to manufacture. Therefore, it was decided to redesign the product so that it could better fulfil the criteria of a volume product.

Various new design criteria are now active in the new design context. A (relatively) low cost criterion is in effect. Ease of assembly is another criterion with increased score. The use of subcontractors in manufacturing was now deemed to be permissible. Also, a nicer external packaging of the product was desired.

Next, the past design process and its decisions must be reconsidered in light of the new criteria. In figure 8 the model during redesign with new criteria is shown (see also comparable figure 4).

Old alternatives are now evaluated against new and changed criteria. The idea of using the electromagnetic actuator still fulfils the criteria and is chosen as the basic technology of controlling the positioner's movement. But the structure needs new ideas, because we can, for example, evaluate the alternative of springs and see that the number of components is too high to fulfil the criterion of design for assembly.



Evaluation:
Working area: lenght of the tooth + SCARA's working area = 12cmx12cm
Accuracy: calculated from control algorithm = 0.2μm
x-axis: length of a tooth = 1.8mm
y-axis: lenght of a tooth = 1.8mm
z-rot: realized by moving x and y
Pollution free: no extra particles
Load: SCARA's max load – mass of magnets = 125g
Suitable for SCARAs interfaces: OK
Finished outlooks depends on housing used.
Design for assembly: number of components = 30
Cost = material costs + manufacturing costs = xx dollars

Figure 8 New criteria in redesign.

7.2 Technology Driven Evolution

At this stage, a technological innovation took place: perhaps an air bearing used in some other pieces of laboratory equipment might be able to do the job?

First, the designer must now evaluate the idea to see whether it suits the positioner design context. The designer reconsiders the issue of the structure and develops the new alternative of air bearing. The model is shown in figure 9 (see also comparable figure 6). From design context the constructor can find all the related decisions and the existing product model, which shows the geometric entities and structure needed by the electromagnetic actuator. Because air bearing needs planar surfaces between the body and armature the teeth must be inserted in slots inside the base material. In the surfaces, there are a few channels from which the air is blown between the surfaces so that they do not touch each other.

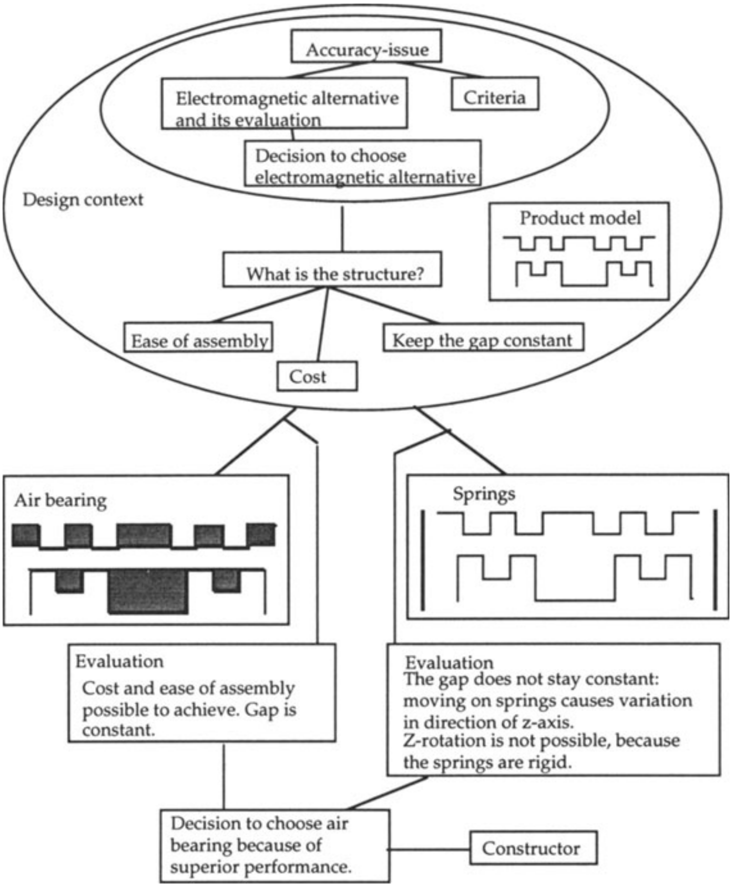


Figure 9 New alternative in redesign.

After developing the new alternative it is re-evaluated against all criteria related to the design context and issue being considered. A new decision is made in which the air bearing solution is chosen, because it is able to rotate along z-axis and it is pollution free.

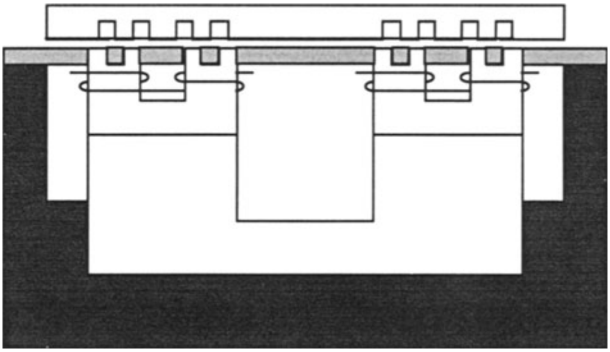


Figure 10 New detail design after redesign.

After the new decisions a new detail design process is again required to determine the detailed shapes of the various components. As result, a new structure of the product which is quite different from the earlier version emerges; see figure 10. Observe that no single component remains from the original design (except for the coils).

7.3 Considerations of Process Driven Evolution

Improving the product design process is usually hard because it is so tightly related to creative work of designers. Our proposed model provides several ways to measure and assess the design process: number of criteria studied during design, number of alternatives considered, and the quality of evaluation methods for the criteria included.

In the case study, the number of criteria used in the first round of design was quite small. This suggests the danger of an incomplete design that fails to consider all relevant issues. Same notes apply to the number of design alternatives considered: potentially superior designs may exist.

8 DISCUSSION

Our work is at an early stage, and few firm conclusions can be made. Instead, we offer some discussion on the work so far.

We expect that the basic concepts of the model are now fairly established. However, the actual information contents is still quite ill-defined. With concept taxonomies, we expect to be able to provide sufficient flexibility to cover many types of models as may be required.

The concept of alternative in our model is not yet firm. There is two possible ways to think about the semantics of alternatives. First, alternatives are general methods to solve problems. For example, when the issue is: we want to restrict the people who can enter to a room, one alternative is to lock the door and give key to them, who are allowed to enter the room. This same idea goes to files, but the names of the matters are little different: form the group of allowed users and give them permission to read and write to the file. According to this approach the alternatives form a library, from which the designer can find possible solutions to issues. This leads to the requirement of being able to model alternatives in a context-free manner somewhat akin to the design pattern approach in software engineering.

In the second approach, alternatives are already applied to the issue, so that it has proven that this alternative really solves the problem. This forms the product model, in which all needed entities are set. In this way, it is assured that all side effects are noticed. In this approach, the burden of reusability is laid on issues instead of the alternatives.

There appear to be two types of criteria in our model: some that relate to the whole process and some which are related to only one issue.

We have not touched too much the issues related to the actual product model. Clearly, we need a model that can show the different versions of product's structure and their relations to each other. Likely, some type of constraint propagation/inheritance is needed to maintain the models.

9 RESEARCH AGENDA FOR FUTURE WORK

The represented model has not yet been implemented in any working system. However, we are planning an industrial project together with some Finnish companies, during the course of which a working prototype of the model will be built, actual design processes modelled, and the resulting models assessed. We will work in close co-operation with a sister project focused on process assessment and improvement and expect useful ideas to emerge from this exchange of information.

In the longer term, we hope to be able to deploy the design process model also in other life-cycle stages besides product development. We are particularly interested in the transition from product development to configuration-controlled design. Here the basic issue is how a product configuration model can be maintained incrementally in accordance to the evolution of the product design. Similar problems emerge from considering other life-cycle activities, in particular production engineering.

Last, user interface of the system must be attractive and the use of this system must be useful, so that designers cannot live without it.

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