CONSTRAINT PROCEDURES FOR COMPUTER AIDED DESIGN

A.J. Medland
Professor of Design Engineering

Department of Mechanical Engineering
University of Bath

Abstract: The nature of creative design makes it impossible to fully define all the design requirements before the activity commences. The process is goal directed in which an understanding of the problems emerge as the activity advances. This aspect of design is thus considered to be aligned to problem solving strategies, in which search techniques are employed to investigate the design space.

Approaches seeking an optimum solution run into difficulties when defining an appropriate fitness function. To overcome such issues a designing environment has been created based upon constraint resolution processes. Here the final design is evaluated in terms of the total truth of the constraint rules derived from the individual design requirements. This will allow mixed parameters and requirements to be specified and resolved.

Keywords: Design systems, problem solvers, search methods, CAD, computer simulation.

1. BACKGROUND

Creative design is a complex, ill-structures and evolving activity. It calls upon experience and creativeness. Rarely is the design fully defined at the outset, so that throughout the activity a greater understanding is obtained and eventually the desired output is achieved.

Even when the design has been accomplished rarely can the activity be claimed to be complete and what has been achieved is fully understood. Often designs will need to be revisited throughout the product development phase and even on into full production. The learning process about the product or design continues right through its life until it is withdrawn.

Considerable research effort has been put into understanding and defining the design process for many years. Some progress has been made in systematic and procedural design [1,2]. As these approaches handle only well structured or well organised design problems they can be expressed on formal terms as relationships or procedures. The creative aspects of designing are still as yet unresolved for the reasons expressed above. It is not a process based or ordered. It is real life and nearer to chaos when viewed in practice.

2. A GOAL DIRECTED VIEW

It is only by adopting a problem solving strategy that such activities can be solved. All problem solving is based on goal searching. Here goals or objectives are defined and searching techniques employed to seek possible solutions (figure 1). No procedure is predefined for the solution. Courses of action are chosen through problem investigation. Any conceived solution (good or bad) is tested against its ability to meet the specified solution goals. The searching strategy is then modified, from knowledge drawn from previous attempts. Improved solutions are then proposed and evaluated.

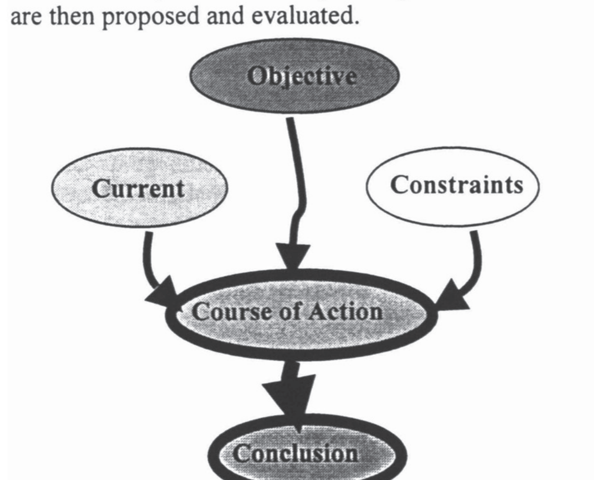

Figure 1. Problem solving structure

All goals set for the solution need to be simultaneously tested. It is insufficient to meet one goal at the expense of all of the other. An acceptable goal is only achieved if all the design constraints are also met. In design these goals and constraints can range from obeying the laws of physics through to financial limits set on the cost of manufacturing, distribution and purchase price.

The designer, operating within a problem solving approach, is thus faced with seeking a solution that successfully satisfies all the known goals and constraints, with no formal procedure that will lead to an ideal solution. To make it even more difficult for the designer, there is no way of knowing whether a solution actually exists for that combination of goals and constraints, without simply searching the complex solution space. And if one does, is there an even better one somewhere in the design space?

3. SEARCHING FOR OPTIMISED DESIGNS

When approaching creative design by problem solving approaches, optimisation techniques are often employed. These can take many forms. They seek to find the optimum value of a declared fitness function. This allows the sought solution to be defined in terms of a single parameter and mathematical processes used to explore the shape and form of the chosen design space.

The problems with the application of optimisation processes in this area of design are many. Firstly the incomplete nature of the activity makes it difficult to develop and maintain a single fitness function throughout the process. The designer is forced at an early stage to concentrate his efforts upon the suitability of the general principles of the design approach and whether it will fit within the structure and concept of the overall product or system. During the later stages the designer focuses upon the detail to ensure that the functions are successfully implemented and they can be manufactured to cost, etc. As more is learnt about the design problem and its constraints (through the process of undertaking the task) the objectives have to evolve and change accordingly.

Additionally there are very few designs in which it is necessary to satisfy only one design goal. Usually success is considered as a combination of a number of, often competing requirements. These may range from technical and physical parameters, through to limits on cost and manufacturing capabilities. They may be continuous functions defining a relationship that must exist throughout the design space, or discontinuous that define the existence of limiting conditions.

If a single multidimensional design space can be derived then the optimum can be found by direct mathematical solution of the derived function or by numerical techniques. The diversity of the goals, and their defining parameters, makes it difficult to create and maintain such a single fitness function, due to the complexity and interrelationships that exist. A weighted fitness function approach is thus often applied.

A weighted fitness function is derived by assuming that a weighted relationship can be maintained between the key parameters and goals throughout the search. This can be undertaken in many ways. Combinations of parameters can be defined and their relationships preserved by dividing one by the other. A solution can be defined as one that has a certain proportion of one attribute and a balancing proportion of another. These can be summed with chosen weightings to create an overall objective function and a solution then sought.

Within a complex and evolving design problem, the creation of such a fitness function is extremely difficult and its effect upon the direction of the search and the form of the final solution can be difficult to predict. If the combination of parameters or weightings are inappropriate then the solution can be dominated by the form of the fitness function rather than by the design problem itself. Dangerous and unstable solutions can be forthcoming that can only be detected through further evaluation and experimentation.

4. CONSTRAINT APPROACH

An alternative approach can be applied based upon the theory of constraints [3]. Here the constraints define individually the requirements that are sought. Each must be testable and when satisfied be in a 'true' state. The approach thus seeks a state in which all requirements (cast as goals) are found to be true.

Solutions are then not necessarily optimal nor are they unique. They are only true against the set goals (or rules). Many other satisfactory solutions may also exist. Conversely no solution may exist as the result of conflicts between the goals.

Whilst the approach is generic and simple, its implementation into a design approach can be complex. Searching a design space formed out of a diverse and conflicting set of parameters, for solutions that comply to many different objectives, can be very difficult. No direct or field search techniques can be guaranteed to find an optimum solution for such a problem. There are no guarantees that they will find any.

The approach is however helped by the practical nature of design. It is not a mathematical or scientific investigation. The designer is looking for possible solutions. Sometimes any solution! Often it is an improved solution to one that already exists. It is rarely an open field in which the designer has no experience. Previous successful designs exit and can be used to 'seed' the search for a better. The designer is reluctant to throw out all previous experience and to start again with a clean sheet. He is then forced to build up a completely new range of experiences.

Design thus, in practice, advances in an evolutionary way towards new ideas and approaches. This can then be used as the starting point for a new search. Often this will be carried out on the basis of minimum changes from the old to meet new objectives. Difficulties in seeking a new solution will both aid the designer in understanding those parameters that will influence the search for a new solution and the sensitivity of the found solution.

If changes in a parameter have little to no effect on the state of the design then it is either independent of, or at least, insensitive to that parameter. On the other hand, if violent changes occur to the solution it can be seen to be highly sensitive to small changes in that parameter. Whether these are desirable or undesirable attributes will be dependent upon the objectives of the design.

Within a constraint resolution approach the designer is not forced to follow a set procedure but to seek solutions that are 'true' according to a defined set of objectives. The designer is free to manipulate and explore both the objective rules and the design variables in a search for a satisfactory solution. Throughout the process, all can be manipulated, changed or added to, in a search for a better solution.

5. CONSTRAINT MODELLING ENVIRONMENT

A designing environment based upon constrain resolution processes has been researched and applied to industrial problems by a group at the University of Bath for the past eighteen years [4]. This has progressed from a simple demonstration of this approach through to a full system integrated with a solid modeller, which in now being marketed by a collaborating company.

Whilst a considerable amount of the research has been centred upon mechanism and machine design, the approach is generic and can be applied to a wide range of design problems. Investigations have been conducted into its application to manufacturing planning and inspection by co-ordinate measuring machines [5]. It has been employed as the controlling and decision making element within complex structural analysis and fluid flow problems, in order to seek balanced solutions to complex problems.

The constraint resolution environment has been generated to allow both constraint rules to be defined and free variables to be declared for their solution. The truth of any rule is declared to be true when its value is zero (it is also a real number, rather than an integer). The overall truth of the problem is then calculated as the square root of the sum of the squares of all the individual truths. This allows the individual rules to be clustered and nested within an overall design solution scheme. The rules can be switched on and off or weighted in order to provide a preferred direction of search but to not effect the finally found solution.

In a similar manner the design variables, applied during the search, can be switched on and off. This allows different sub-problems to be investigated or regions of the design space to be restricted during the search.
A number of direct search and advanced searching techniques have been investigated and plans are underway to incorporate some new ones within the designing environment. In the main areas of application it has been found sufficient to employ a modified Powell approach. This is in principle a valley seeking technique in which the local direction of search is systematically modified as the search progresses. It also incorporates techniques to bound or limit the parameter values and has the ability to take random steps if a local minima is detected.

Whilst such a searching approach is relatively unsophisticated it requires little knowledge of the design space in order to search for a solution. When the problem is incomplete or conflicts exist it will rapidly terminate. Whilst it may miss solutions in a complex and 'hilly' field, the designer is usually looking for more stable solutions in an insensitive region. The approach may thus miss some extreme solutions but will allow the designer to find acceptable ones if they exist.

6. EXAMPLE CASE STUDIES

Within the MAFF LINK investigation AFM21, "An investigation of a redesign methodology for packaging machinery" a number of machines were investigated and redesigns proposed on the basis of the constraint approach [6].

Each machine was studied holistically and an approach developed (Figure 2). The knowledge held by the company designers was extracted through discussions and brain storming sessions. An understanding of the historical developments and modifications occurring to meet new goals allowed constraint models to be built of the critical regions of the machines. In parallel an experimental investigation was conducted of each machine using a high-speed digital video camera and accelerometers [7]. The data achieved from both the constraint based models and the experiments were then compared. Errors were discussed, models refined and new experiments conducted until good correlation was achieved between the techniques.

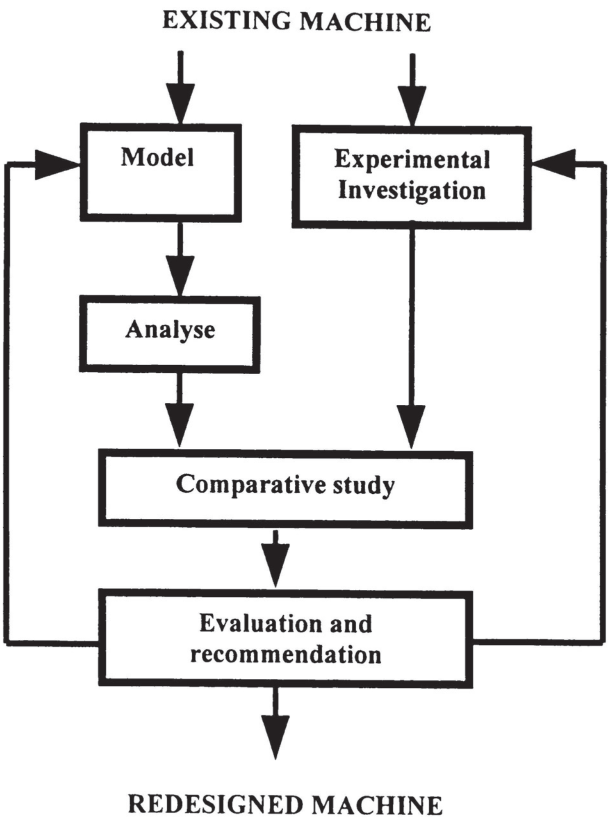

Figure 2. Redesign methodology

This initial part of the investigation provided the necessary level of understanding of the current machine design upon which changes could be based.

Within the study three classes of change were defined leading to different levels of redesign (Figure 3).

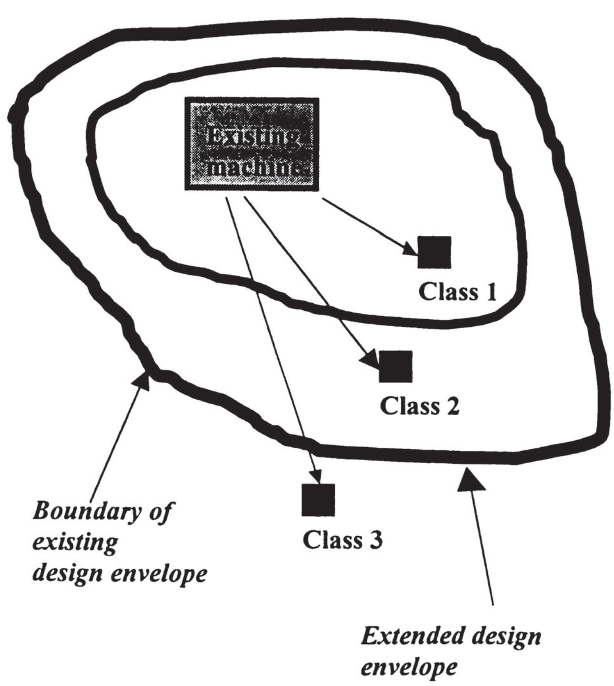

Figure 3. Levels of redesign

6.1 Class1

The first was when it was possible to achieve the desired design improvement within the existing design envelope. The machine principles and topology remained unchanged. A solution was sought by only changing parametrically the geometry of individual components and their settings.

Figure 4 shows such a redesign in which the performance of a pushing mechanism was improved. The problem arose when it was discovered that the product was being damaged during the pushing operation. A visual study confirmed the prediction of the constraint model that the motion of the pusher both accelerated and ducked down towards the end of its travel, causing the product damage.

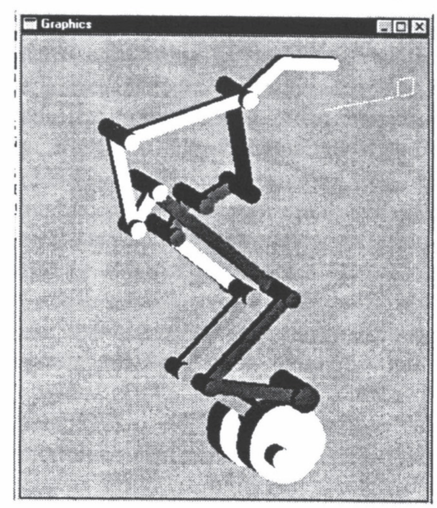

Figure 4 Class 1 redesign

A preferred motion was derived and applied as the driving condition for the constraint model. Settings and link lengths were chosen to provide the best configuration throughout the operating cycle. The model was then run in reverse to allow a new set of cams to be generated. These when rerun in the model showing a reduction to less than a third in the pushing acceleration and no diving of the end motion. All of this was achieved within the same machine constraints and cycle time.

Modified cams were cut and installed in the machine. An investigation showed that the machine then performed as predicted.

6.2 Class 2

In the second class of redesign the investigation showed that the performance improvements could not be achieved within the existing design envelope. A further study showed that a single device within the machine was limiting the performance. Here improvements were achieved by undertaking the redesign of that single unit.

Figure 5 shows such a packaging machine in which a folding mechanism was found to restrict the machine performance. A new approach was applied to the operation of this device and a sub-assembly designed to fit within the existing space and being triggered by the same actuation system.

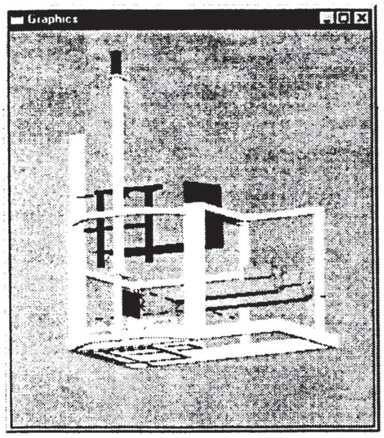

Figure 5 Class 2 redesign

The feasibility of this solution was demonstrated in principle and through prototype development.

6.3 Class 3

The final class of redesign was considered in which a number of internal mechanisms or devices are demonstrated to be incapable of improvement to meet the new requirements. Changes in any of these devices alone would not provide the sought for improvements. This could only be achieved by extending the design space and creating a completely new design that satisfied all of the old requirements as well as the new.

Figure 6 shows such a new design in which a completely new transfer turret was designed to replace an existing unit. Here the transfer motion was required to match the existing motions and orientations whilst minimising acceleration and jerk. The new device was also required, in the event of a malfunction to disengage safely.

Figure 6 Class 3 redesign

7. CONCLUSIONS

The constraint modelling approach has been shown to aid in the design and resolution of complex and ill-defined problems. Whilst not seeking to find an optimised solution, it was created to allow satisfactory solutions to be achieved. It seeks to establish a design state in which all requirements are deemed to be true.

Such an approach allows the designer to investigate new ideas during the creative stages of design. Constraints and rules can then be allowed to evolve throughout the process and solutions sought for in preferred regions of the design space.

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