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APPROACHING DESIGN THROUGH SENSITIVITY

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Abstract: *Considerable effort has recently been put into approaches for the optimisation of design configurations. These, however, require that a single objective function be created to define the optimisation parameter. This both requires that the relationships (or weightings) between design parameters are determined prior to designing, and that the optimising function is continuous across the design space. In real, complex and evolving design problems this will not be the case.*
Current research into constraint resolution procedures has led to the investigation of the use of sensitivity in the solution of designing problems. The approach proceeds, from an initial 'seed' position within the design domain, by investigating the influence of all variables upon all of the design rules. From this sensitivity study those parameters having little, to no, effect can be eliminated from the initial search and the key ones selected. The approach then evaluates the 'truth' of the solution found against the 'goal'. If this is not sufficiently true the study is repeated (using the new solution point as the seed) and new design variables are found and applied in the search.
Within this research programme a number of examples, ranging from simple to complex, have been undertaken, which are used to illustrate the theory and application of this approach.

1. BACKGROUND

Recently there has been considerable effort within the design research community into the generation of techniques for the optimisation of design configurations [1,2]. This work is mostly centred on the formation of a single objective function that can be used to express the relationship between the design parameters. The creation of such a function presupposes that the problem is fully understood and that the relationships between the various objectives are also unchangeable throughout the problem resolution. The design problem must thus be fully understood before any optimisation can be undertaken, and that no objectives are changed, in the light of what has been learnt during the designing process. This requires that all the relationships (or weightings) between design parameters and objectives are determined prior to designing, and that the optimising function is continuous across the design space. In real, complex and evolving design problems this will not be the case.

1.1. Problem solving approach to design

Design is an ill-structured, incomplete and evolving activity, which is focused upon the resolution of an often ill-defined problem (or set of objectives). It, therefore, contains all of the elements of a classical problem solving structure [3]. These are (as shown in Figure 1) a current state (where one starts), an objective state (what one is trying to achieve), a set of constraints (which will stop one achieving that goal), a proposed course of action (an attempted approach to the solution) and a set of conclusions (that establish whether the objective state has been reached or not).

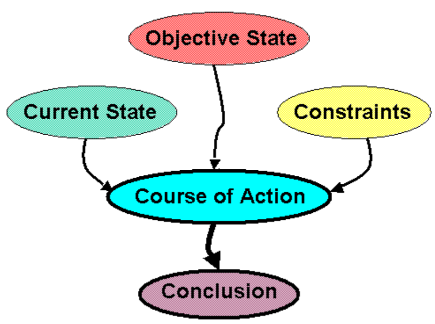


Fig. 1. Elements of problem solving.

2. CONSTRAINT RESOLUTION TECHNIQUE

The constraint resolution approach is based upon the assumption that a problem can be defined as a series of propositions that are formed as design rules, which are to be true when the problem is resolved. The design variables are manipulated, by direct search techniques, in order to seek a state when all these rules are true [4].

The problem can be formed in many ways. A series of sub-problems can be formed, with their own design variables, and the problem addressed as a sequential series of elements (such as can occur in the resolution of a mechanism train; starting with the input crank angle and working progressively through the sequence of linkages until the output is reached). These sub-problems may, at a higher level, be nested within other overall problem requirements (such as can occur when the output performance of such a mechanism has to be optimised) [5].

At the highest level it can be assumed that all design variables have an influence upon all of the design rules. In this case, a single complex problem function is formed with a search being conducted through the domain covered by all of the variables (Figure 2). When the problem is of limited size, in both rules and variables, this may be resolvable by direct search techniques. If, however, it is large in both dimensions, and the relationship matrix sparse, then it may be difficult to resolve by such search techniques. This may, however, be achievable by the investigation of the problem sensitivity.

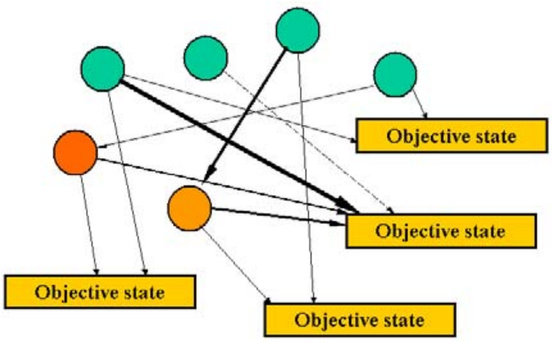


Fig.2. Complex problem of multi-related variables and objective states.

2.1. Sensitivity structures

In many problems some of the design variables only have an influence on particular aspects of the local problem. In other design investigations it may appear that it is right to 'assume' that certain variables will have a great effect on the solution and it may turn out not to be the case. Similarly the design may commence with some of the variables already true (ie. they do not have to be manipulated). This can always be the case when the design problem is incomplete and evolving.

Within such problems it is necessary to develop initially an understanding of the design issues, and the effect of the initial parameters and approach upon the solution. This is effectively commencing by understanding the region around the 'current state' of the problem solving model. A sensitivity approach can be used to determine such effects by calculation of the steepness of the gradient of changes in individual parameters upon each individual requirement, and upon the overall objective.

The sensitivity approach thus commences, not by directly seeking a solution, but by trying to understand the influence of the design variables upon the truth of the initial 'seed', or initial starting configuration, chosen within the design domain [6,7]. By following the classical problem solving approach, knowledge is gathered around the region of the initial starting point in the design domain by changing the design variables, in order to determine how they aid the achievement of the 'objective state'.

The direct search approach of constraint modelling proceeds by determining the influence of each variable upon the solution, and hence determines the resultant vector direction that should be taken (from that point) in search of a true solution. The sensitivity variation (Figure 3) commences in a similar manner by looking at the influence of all variables on all rules, but then proceeding, not by determining the resultant vector direction, but by selecting and applying, initially, only those variables that have a dominant influence upon the solution. Once these variables have been applied to the solution, a new 'current state' is determined, which may or may not solve the problem. If the solution is not 'sufficiently true' then the approach is repeated with perhaps a lower value of dominance (ie. allowing a greater number of variables to be included in the solution).

Through this approach complex problems can be searched and resolved, some times through the application of very few design variables. The actual number of variables ultimately employed is dependent upon a number of factors. The initial state may, by chance, be close to a true state. Only a limited number of variables may need to be changed to achieve this true state. Conversely the initial state may be in a remote part of the design domain, far away from the true solution, and therefore require a complex and extensive search through most of the variables. Additionally the variables influencing the changes in the initial state may be quite different to those influencing the final true state.

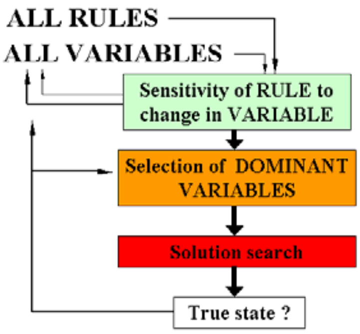


Fig.3. Sensitivity analysis approach.

2.2. Sensitivity understanding

The availability of the sensitivity values, and knowledge of the boundary conditions of the variables and rules, allows the designer to determine whether any changes in these parameters will result in the design exceeding a boundary condition or for a rule to fail. Such an approach provides the designer with a range of additional information and greater understanding of the problem, and may lead to possible alternative solutions being investigated. Rather than simply being presented with a single design (that may or may not work in practice), the designer is aware of how sensitive the design is to geometric variations and the effect of the individual rules.

2.3. Sensitivity studies

Such an approach can be applied to a wide range of design problems. It has been used as a technique for handling complex and conflicting issues within multi-disciplinary teams, in which responsibilities and understanding of the individuals are limited to their own aspects. Currently the approach is being investigated within a project that is undertaking the design of medical devices. Here the size and form of the device has to meet conflicting requirements of medical usage, patient acceptability, manufacture, safety and disposability. These result in conflicts to be resolved by the team, which can be guided by the study of the sensitivity of the parameters to the various conflicting issues. A set of variables is sought in which all requirements are met and no 'untrue' states remain.

In a simple design study the rules were collected for the design of a bicycle [8]. This was described parametrically as shown in Figure 4 and the rule set as in Figure 5.

These rules were collected by simply asking various people what they required of a bicycle. There was no attempt made to determine whether individual rules were in conflict or duplication of others.

Additionally there was no attempt made to ensure that the rule set was complete (this set is known to be incomplete as further work should be performed to ensure both the stability and comfort for the rider).

These rules were, however, analysed to determine the sensitivity of individual rules to each variable. This study shows (in Figure 6) both the resulting sensitivity matrix and a number of design configurations that resulted through the manipulation of the rules and reduction of the design variables.

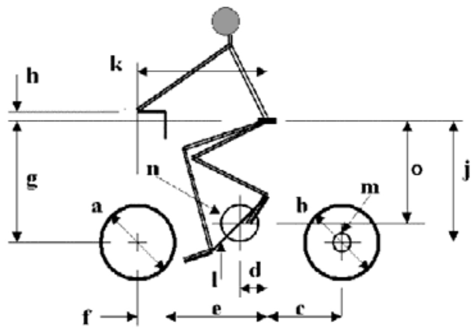
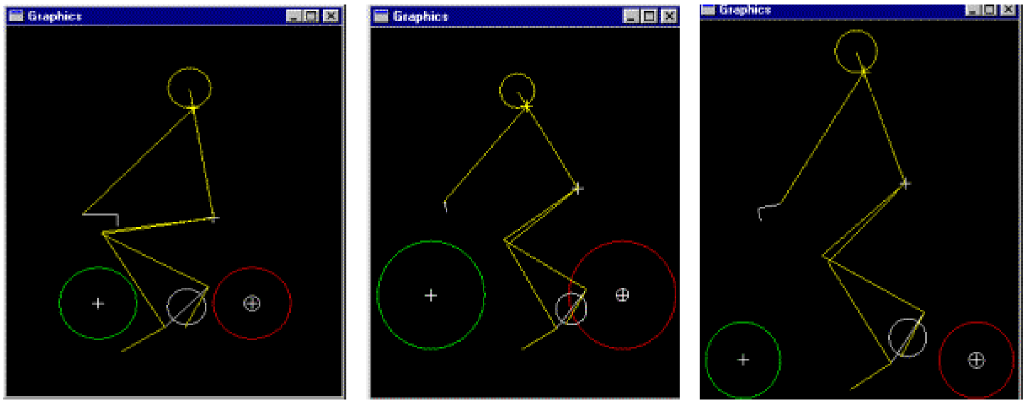


Fig. 4. Parametric description of a bicycle

rule 1	reach the handlebars	(par_k .le. att1*(par_Cb + par_Db))
rule 2	handlebars in front of forks	(par_k .gt. par_e)
rule 3	knees not into forks	(par_Bb .le. par_e)
rule 4	front wheel close to handlebars	(par_f .lt. att2*(par_k - par_e))
rule 5	legs reach bottom of stroke	((par_Ab + par_Bb) .gt. (par_o + par_l))
rule 6	legs reach top of stroke	(par_o - par_l) .gt. ((par_Ab + par_Bb)/2))
rule 7	feet clear of the ground	((xa*xb)/xc) .gt. (xd + att3*par_Eb))
rule 8	front wheel under stem	(par_a .le. par_g)
rule 9	front wheel > 0.5 stem height	(par_a .gt. 0.5*par_g)
rule 10	rear wheel under seat	(par_b .le. par_j)
rule 11	rear wheel > 0.5 saddle height	(par_b .gt. 0.5*par_j)
rule 12	sprocket < rear wheel	(par_m .le. par_b)
rule 13	sprocket > 0.5 rear wheel	(par_m .gt. 0.05*par_b)
rule 14	sprocket < chain wheel	(att5*par_m .le. par_n)
rule 15	chain wheel < pedals	(par_n .le. par_l)
rule 16	chain wheel > o.5 pedals	(par_n .gt. 0.5*par_l)
rule 17	wheels do not clash	((par_a + par_b) .lt. xc)
rule 18	pedal spindle infront of rear wheel	((par_c + 1.1*par_d) .gt. par_b)
rule 19	front wheel < 2 rear wheel	(par_a .lt. 2*par_b)
rule 20	rear wheel < 1.25 front wheel	(par_b .lt. 1.25*par_a)
rule 21	feet can reach the ground	(par_Ab+par_Bb) .gt. (par_j+par_b))*1000
rule 22	stem < 1.25 saddle	(par_g .lt. 1.25*par_j)
rule 23	saddle < 1.25 stem	(par_j .lt. 1.25*par_g)
rule 24	foot not into front wheel	((par_d+par_l+par_Ed) .lt. (par_e+par_f-par_a))*1000
rule 25	chain wheel infront of saddle	(par_d .gt. 0)*1000
rule 26	dist.to front wheel > thigh length	(par_e .gt. Par_Bb)*1000
rule 27	limit how far wheel out the back	(par_c .lt. Att4*par_b)
rule 28	set attitude to pedals	(par_d - (par_o*tan(tilt)))

Fig. 5. Rule group collected for a bicycle



TRUTH	0	0	0	3	0	0	0	0	0	0	1	0	0	0
RULES	rule 1	rule 2	rule 3	rule 4	rule 5	rule 6	rule 7	rule 8	rule 9	rule 10	rule 11	rule 12	rule 13	rule 14
variables														
par_a	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_b	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_c	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_d	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_e	0	0	1	1	1	0	0	0	0	0	0	0	0	0
par_f	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_g	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_h	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_i	0	0	0	0	0	1	0	0	0	0	0	0	0	0
par_j	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_k	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_l	0	0	0	0	0	1	1	1	1	1	1	1	1	1
par_m	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_n	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ht	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TRUTH	0	0	0	0	0	0	0	0	1	0	0	0	0	2
RULES	rule 15	rule 16	rule 17	rule 18	rule 19	rule 20	rule 21	rule 22	rule 23	rule 24	rule 25	rule 26	rule 27	rule 28
variables														
par_a	0	0	0	0	0	0	0	0	0	1.000	1.000	0.333	0.333	0.333
par_b	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_c	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_d	0	0	0	0	0	0	0	0	0	1.000	1.000	0.333	0.333	0.333
par_e	0	0	0	0	0	0	0	0	0	1.000	1.000	1.943	1.943	1.943
par_f	0	0	0	0	0	0	0	0	0	1.000	1.000	0.333	0.333	0.333
par_g	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_h	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_i	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_j	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_k	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_l	1	1	1	1	1	1	1	1	1	1.000	1.000	0.333	0.333	0.333
par_m	0	0	0	0	0	0	0	0	0	0	0	0	0	0
par_n	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ht	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 6. Sensitivity relationship matrix and alternative design solutions

This approach allowed the problem to be reduced to a number of sub-problems in which different variables dominated to allow a solution, whilst being overall 'true' according to the rules, approached the solution in different 'directions' by considering different aspects of the bicycle to be more dominant than others. The solutions show an adult trying to ride what is a child's bicycle and showing the compromises the adult has to make in order to achieve a riding position. The other two images show solutions, for the same adult, when either 'standard' or 'small' wheels are required.

Whilst this problem is seen to be manipulating only twelve parametric variables it can allow the designer to create a wide variety of solutions tailored to different requirements. However, in another study the sensitivity approach was applied in the determination of human postures when operating a packaging machine (figure 7).

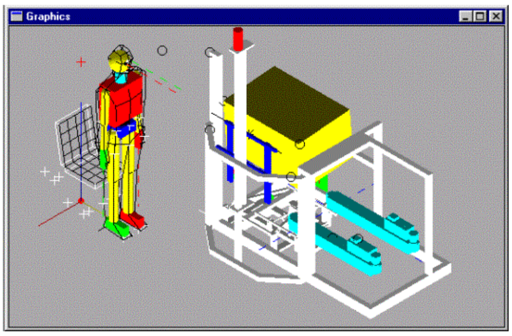


Fig. 7. Models of man and packaging machine

In this study both the manikin and machine were built within the constraint modelling environment. The machine can thus be made to work and the man respond to human actions and mobility. This human representation is comprised of 144 degrees of freedom that can be individually manipulated in order to find a suitable posture. There are 172 bounded constraints that either limit or restrict the range of possible movements within the joints. Additionally there are 22 rules that can be applied to general human conditions, such as standing, sitting, balance etc. These can then be configured to allow individual tasks and intermediate actions to be determined.

Figure 8 shows the man sitting on a chair, whilst pointing and looking at a point high upon the front of the machine. This task is seen to be one that can be readily solved through the sensitivity approach with a restricted set of variables. If, however, a more difficult task is set in which no simply true solution exists, then the sensitivity approach will select variables (degrees of freedom of the manikin) and rules that will lead to a solution in which not all rule sets are true.

In Figure 9 the man has been set the task of looking at a point underneath the main body of the machine.

In this solution the sensitivity approach has elected to allow the manikin to remain in contact with the chair and floor, whilst being able to both point and look at the designated point on the machine. It has, however, abandoned the normal requirements of sitting and leaning back in the chair and the normal attitude in which both feet are flat on the floor. Whilst this may not be an expected, or normal, posture for a human to take when working at a machine, it is nevertheless a possible configuration for a human to take if required.

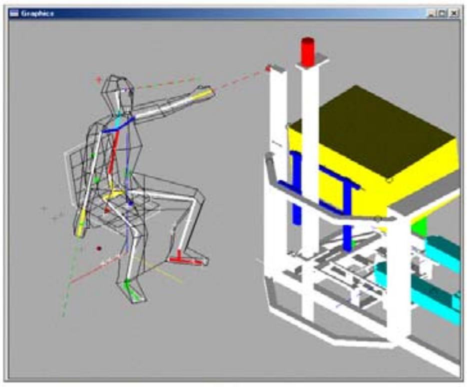


Fig. 8. Man pointing whilst sitting whilst pointing and looking toward a point high on the front of the machine

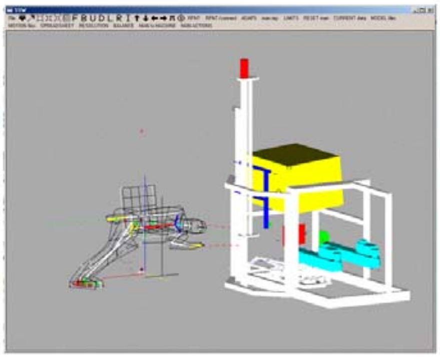


Fig. 9. Man trying to view a point under the machine

The sensitivity approach can thus be used to determine both a range of possible solutions and those that may be possible if certain sets of rules are abandoned or modified. It thus has the potential to aid the designer in the search for creative and innovative solutions to problems.

3. MULTI-INSTANCE MODELLING

The sensitivity approach, like that of constraint resolution techniques, takes advantage of the direct searching of the individual variables to learn more about the design domain within which it is operating. The constraint modeller learns about the curvature of the domain, in order to seek a point at which a true solution exists (this may not, however, be the only true point). The sensitivity technique obtains information on the relationship between all rules and variables, in order to build up a more complete understanding of the design domain as the solution advances.

This approach is now being extended even further through research into multi-instance modelling (MIM). Here not only is the design domain searched around the region of a true solution, but multiple regions are sought. The MIM approach thus seeks the possibility of finding a range of possible solutions to a problem. In addition the direct search technique, used in the sensitivity studies, will allow the extent of the 'true region' around each point to be determined. This allows investigations to be conducted into the allowable variation in design parameter whilst the solution still remains true.

A study is now commencing into the application of this approach within processing and assembly plant industries, with particular applications in the food sector. This builds on, and extends research currently being undertaken, into the redesign of packaging machinery [9]. The sensitivity and influence of parameter changes on both the product and processes will be studied. This will allow plant of the greatest flexibility to be created, changes made to product with minimal change to plant or, conversely, will allow the limitation of the existing plant to be determined and the range of usage determined. The range of possible product size and type can be established for an existing machine, or the changes necessary to allow machines to cope with a desired increase in product capability and form. This will extend the research into both plant capability and the effects of product changes.

3.1. Research issues

The extension of the constraint modelling capabilities to be able to handle the research into sensitivity analysis has resulted in major changes in the approach. This has not only resulted in the inclusion of routines to calculate the sensitivity parameters and the sensitivity matrix for the complete rule/variable set, but has required research to be commenced into strategies for handling and interpreting the design approach that has to be taken. It is insufficient to rely simply upon the automatic selection of the design parameters. An understanding of the functionality of the problem needs also to be included, as well as the desired direction and preferences of the designer, business and customers. This will then result in the development of techniques to handle and incorporate rules that are neither mathematical nor geometric, as currently handled by the constraint modeller. A more holistic approach is thus sought to the generation and resolution of design rules.

4. CONCLUSIONS

A fundamental approach based upon problem solving structures has shown that design issues can be addressed by, initially, constraint resolution techniques. It has then, through the addition of sensitivity analysis, been extended into the handling of complex and ill-structured problems. These have allowed large and uncertain problems to be attempted and solutions obtained. These have provided a broader base of understanding for the designer and allowed new and creative solutions to be found.

It has also created an understanding of design and approaches, that have allowed further research to be undertaken into these design issues, where both variations in product and processes need to be addressed.

Research in these areas is thus continuing through the constraint modelling approach, together with the application of these techniques to real industrial problems.

Acknowledgements
The ideas within the paper have arisen through progressive research undertaken into the constraint modelling approach to design over the last twenty-five years. Throughout this period the research group, initially at Brunel University, and then at the University of Bath have been supported by research grants from the EPSRC, DTI, IMI, TCS, DEFRA, IMRC and a group of collaborating companies that now exceeds thirty. Without their support this work could not have been undertaken. For this we are very grateful.

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