

# BROWSING A LARGE SOLUTION SPACE IN BREADTH AND DEPTH

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*Computer aided design; Conceptual design; Functional synthesis; Clustering; Visual information exploration.*

## 1 Introduction

It is often noted [1, 2] that designers only explore a few solutions in depth at the conceptual stage. Despite this, evidence suggests that a thorough exploration of a solution space is more likely to lead to designs of higher quality [3,4]. The DESYN system exhaustively generates a set of concepts in the mechanical design domain. The large number of ideas so generated are summarised and presented to the designer for exploration and evaluation. This paper describes methods being developed to enable the designer to navigate and visualise this solution space. Preliminary evaluation of these methods has been carried out by obtaining six designers' groupings of two solutions sets and comparing them to the system's clusterings.

## 2 The DESYN system

### 2.1 Background & Rationale

DESYN is based on FuncSION [5], which synthesises solutions to a class of mechanical design problems involving transmission and transformation of mechanical forces and motions that are specified as inputs and outputs. DESYN uses a set of primary functional elements along with combination rules to create an exhaustive set of solutions in terms of their topological and spatial configurations. Previous research [5] has demonstrated FuncSION's potential for generating novel solution ideas that designers had not thought of. However, it was found that the large number of ideas it generated could not be meaningfully explored, while their representation proved too abstract to visualise. Effective support for conceptual design should help designers to obtain a thorough overview of the solution space, as well as a detailed understanding of its individual solutions. However, the greater the variety and number of solutions to be explored, the less likely it is that a detailed understanding of the potential of all individual solutions will be achieved.

The problem of exploring large combinatorial spaces is an unresolved issue in computer-aided synthesis research [6]. There is also a parallel problem in the display of large quantities of hierarchical information. Users may display navigational uncertainty when multiple hierarchical screens are used, while attempts at overview can be swamped by the volume of information to be displayed [7, 8]. DESYN implements a novel method of clustering the solution configurations to reduce the space of solutions that the designer needs to consider. This is done by presenting the designer with representative solutions that are by-products of the clustering process. In this way, large numbers of solutions can be summarised by a small

number of cluster exemplars or prototypes. Evidence from cognitive psychology provides some justification for the use of representative prototypes for internal categories of solutions [9]. In conjunction with this, DESYN implements 3D visualisation for displaying an overview of the solution space and the spatial layouts of selected solutions resulting from the synthesis.

## 2.2 System overview

1. A requirement specification tool is implemented as a 3D graphic representing the spatial relationships between input and outputs together with entities representing properties such as port type, effort and flow senses and nominal directions of rotation. These properties may also be entered into a text-based dialogue in terms of input/output locations, senses and directions.
2. A functional synthesis module. The specifications are passed to this tool that generates an exhaustive list of all the solutions. Each solution is specified as a coded list of functional elements and their connectivity in terms of input and output relationships. Solution space browsing and clustering then enables the user to select a sub-set of these solutions for further synthesis. The output of this is a list of solutions annotated with orientation and direction information in a pre-defined orthogonal coordinate system.
3. The browsing and clustering tool takes a solution list from the synthesis module as input and displays the list in readable English form. At present, this tool acts as a test-bed for a number of alternative feature descriptions and clustering methods. Clustering is performed after a feature analysis of the solutions is carried out. The present paper reports initial evaluation of a paired-element feature measure followed by clustering using the Partitioning around Medoids algorithm described by Kaufmann and Rousseeuw [10]. Different clustering methods are possible including hierarchical-agglomerative and fuzzy clustering.
4. Once a sub-set of solutions of interest to the designer have been selected, the 3D solution visualisation tool provides a 3D pin-diagram representation of individual solutions. This allows manipulation of 3D view-point of these, sometimes complex, mechanism chains.
5. The 3D solution space visualiser then displays the selected solutions in a single space and allows visualisation of the tree of alternative embodiments as well as the designers' choice of mechanisms for specific solutions. These solutions are then suitable for passing to other systems [11] for development and simulation of the chosen mechanisms.

## 2.3 Validation

A number of levels of validation are proposed at this stage of development of the system. Do designers find the system's clusterings of solutions intuitive and do the clusterings suggested by the system correspond to designers' own partition of the solution space? Initial experiments examined a number of DESYN clusterings of two ~20 solution sets resulting from syntheses that used up to five elements per solution from a database of up to four elements. Clustering was based on an element-pair feature count. These problems are too large to illustrate here. However, Figure 1 is a diagram of the outputs of the clustering algorithm for a smaller 6 solution set synthesised from a three-element database containing wedge, cam and lever mechanisms.

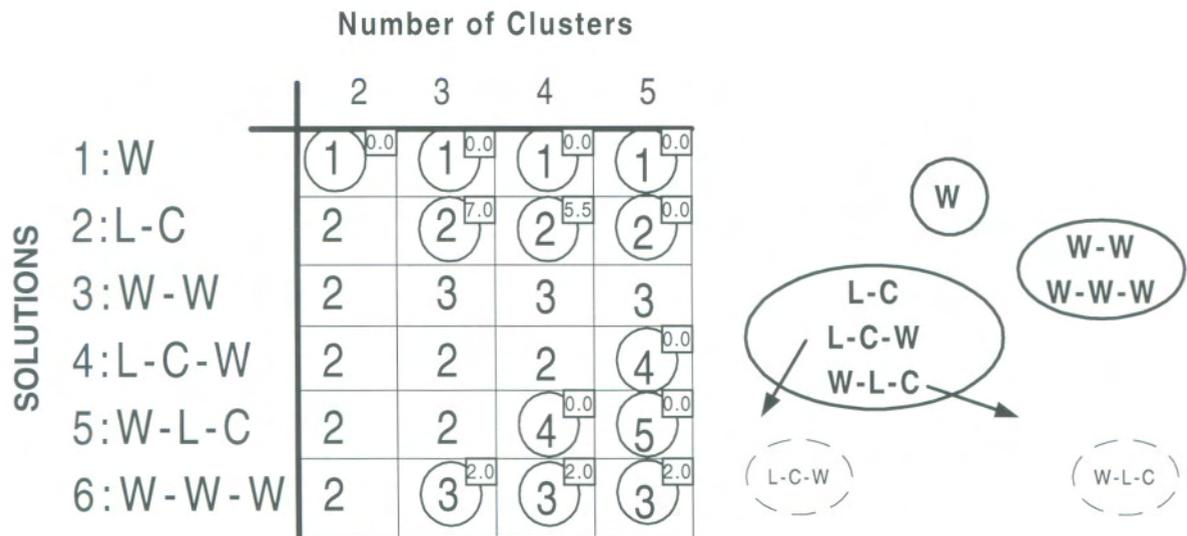


Figure 1. Cluster table for 2 to 5 clusterings of the 6 solutions for a problem using Wedge, Cam and Lever elements. The arrows indicate the solutions that leave the 3 cluster solution to form new clusters.

On the left of the diagram the six possible solutions output by the synthesiser are enumerated. The vertical columns show increasing number of clusters in the solution set. The cells show the cluster membership for each solution. Each cluster has a representative solution that is denoted by circling. Finally, the box in the corner of cells shows the average distance of the representative to all the other members of the cluster. The right hand diagram shows a Venn type representation of the 3,4 and 5 cluster solutions. Solution sets for the larger 5 element problems were presented to 5 subjects as printed words with illustrative diagrams.

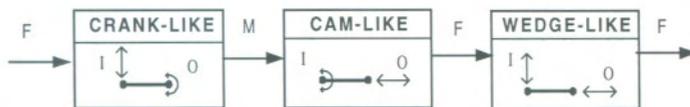


Figure 2. An example of a solution sequence from a solution set presented to subjects.

Subjects were required to form groupings of the 20 solutions that corresponded to their judgements of those that seemed to them to be similar on the basis of their engineering experience. The subject's groupings were scored for the percentage similarity of groupings with the DESYN clusterings of the same set. This was achieved by counting the number of common solutions in the DESYN clustering of the same number of groups as the subject's response. Three measures were used and tested on random data groupings for comparison. All gave comparable values. The results indicated a 69% commonality of solutions for problem 1 and a 80% commonality for problem 2, giving an average of 74%. Random clusterings tested gave an average value of 55%. This indicates a high level of agreement between the DESYN and Human clusterings. Two main strategies were observed in use by the subjects. These were either, grouping by presence of element combinations or, grouping by perceived force manipulations.

### 3 Conclusion

Development of the DESYN system has resulted in a core capability of functional synthesis at the kind level that is followed by clustering of up to 2000 solutions into arbitrary number of clusters, together with representative solutions for each cluster. Initial validation examined a number of DESYN clusterings of two ~20 solution sets resulting from syntheses that used up to five elements per solution from a database of up to four elements. Clustering was based on an element-pair feature count. The results are promising, with clusterings being in agreement with designers' engineering judgements. As the system develops further, validation using real design problems will be carried out.

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